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Waterborne Materials Exchange Between Marshes and Open Water of the Barataria Bay Estuary of Louisiana, United States of America.

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WATERBORNE MATERIALS EXCHANGE BETWEEN MARSHES AND OPEN WATER OF THE BARATARIA BAY ESTUARY OF LOUISIANA, U.S.A.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

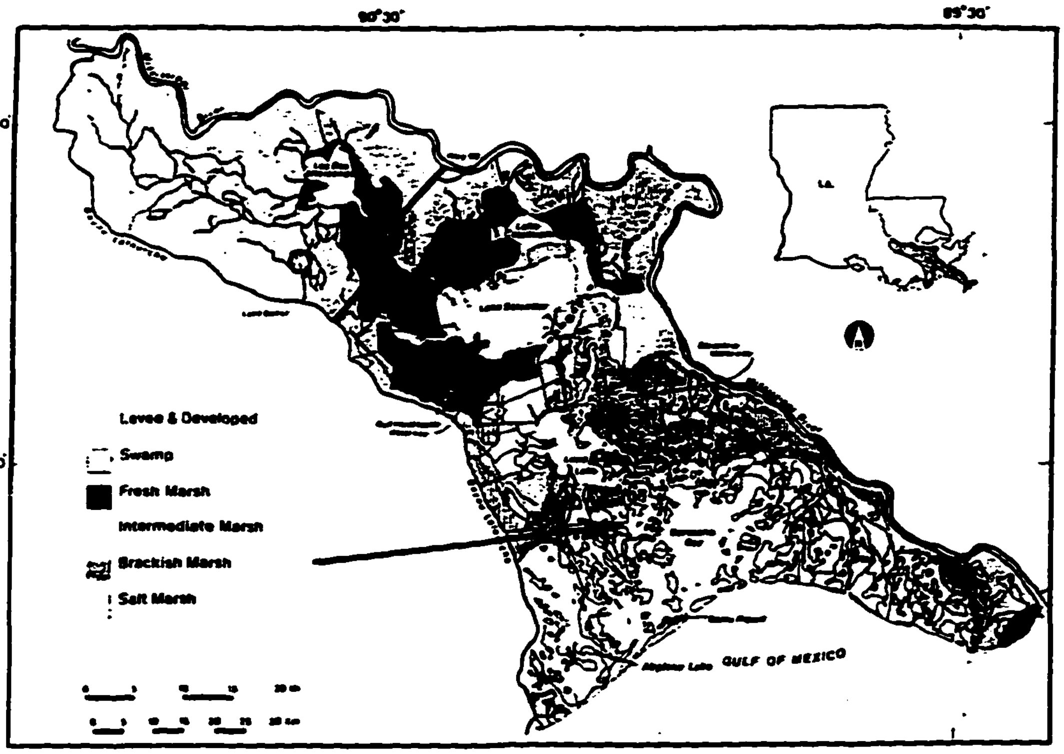
The exchange of carbon, sediment, and water between brackish marshes and a shallow, fine-grained bay of the Barataria Bay Estuary were examined in order to quantify the production, transport, and storage of carbon in the Barataria Basin. Factors controlling these exchanges were identified and measured. Flux of suspended sediments through a tidal bayou connecting marshes and open waters were measured throughout the year and during a variety of weather events. Discharge of porewater from the marsh substrate to surrounding waters via subsurface flows and surficial drainage channels were measured. Constituent concentrations in the marsh runoff were monitored and used to distinguish porewaters from surface waters. Results indicated that the bayou discharges sediment during typical summer conditions and imports sediment during winter. Late summer storms, occurring during the annual period of highest water level, are the largest sedimentary events and result in large net imports of sediment. The bayou/marsh system is a net importer of sediments from the bay. Sediment flux is controlled by water level in relationship to marsh surface elevation, wind speed, direction, and duration, tidal prism volume, and seasonal factors such as invertebrate activity in the marsh. An extensive network of surficial channels or rivulets exists on the marsh surface, resulting in porewater discharge from parts of the marsh that are distant from the bayou. Porewater seepage into rivulets cannot account for the volume of discharge observed. Diffusion of porewater constituents into a thin surface layer of water and flow of the layer toward the rivulet is suggested as the primary route of constituent discharge.

CHAPTER 1. WATERBORNE MATERIALS FLUXES BETWEEN MARSHES AND OPEN WATERS OF LOUISIANA'S BARATARIA BAY ESTUARY: INTRODUCTION

INTRODUCTION

This study was initiated as a part of a larger project funded through NASA's EPSCoR Program. The larger project, entitled "Carbon Cycling and Hydrology in a Shallow Coastal Estuary," aimed to quantify the production, transport, and storage of carbon in the Barataria Basin. As part of this goal, the research reported here was designed to quantify and to identify important physical controls on carbon and sediment transport between tidal marshes and open waters of the basin. To this end a tidal bayou typical of the salt marshes of Barataria Basin was chosen as a primary study site. Ugly Shack Bayou drains a salt marsh bordering Live Oak Bay, a small saline embayment in the northwest portion of Barataria Bay (Fig. 1).

Sediment and particulate carbon are transported between tidal marshes and open waters via tidal channels that are ubiquitous in tidal marshes. Such transport has been studied in a variety of locations on the United States Atlantic Coast (Settlemyre and Gardner 1977; Valiela et al. 1978; Ward 1981; Stevenson et al. 1985; Jordan et al. 1986; Yelverton and Hackney 1986; Zarillo 1986; Wolaver and Spurrier 1988; Roman and Daiber 1989), but has not been extensively studied in Louisiana despite its recognized importance in the building and maintenance of marsh soils and prevention of land loss. Therefore, a study of particulate flux between marshes and open waters was chosen as part of this larger project. Interstitial porewater in marsh soil is known to contain high concentrations of a variety of substances including



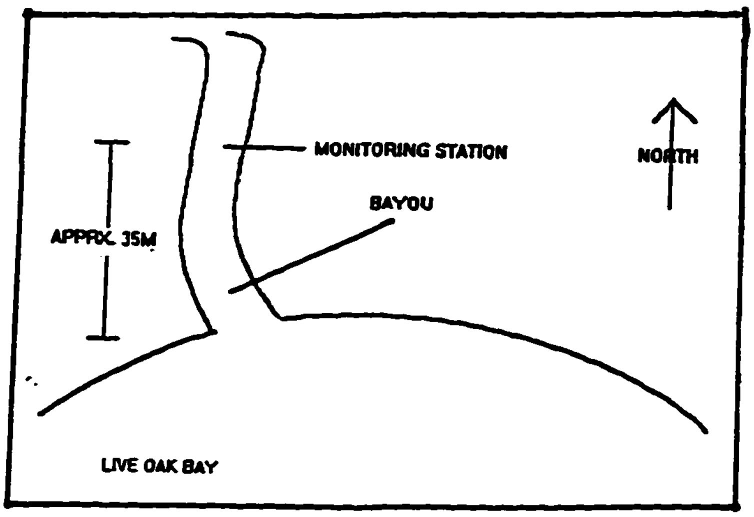


Figure 1. Map of the study site. Arrow in upper figure (DeLaune et al. 1990) indicates location of inset (Denmon 1996).

dissolved organic carbon, metals, and nutrients (Mitsch and Gosselink 1993). The export of these substances from tidal marshes has the potential to significantly impact carbon and nutrient budgets in the Barataria Basin both directly and indirectly. An export of dissolved carbon from marsh soils would represent a loss of carbon from storage and an input of carbon to open waters, while nutrients and metals have the potential to impact productivity both in marshes and in open waters of the basin. Furthermore, porewater movement and export have been very little studied in Louisiana marshes. Therefore, a study of porewater export from marshes was included as part of this investigation. The two processes studied here, particulate sediment flux in a salt marsh tidal channel and porewater flux from marshes adjacent to the bayou, represent the main hydrologically controlled mechanisms of carbon and sediment exchange between marshes and open waters in coastal Louisiana, and thus this study is a complete examination of the major hydrologic processes influencing sediment and carbon budgets of tidal marshes in the Barataria Basin.

This dissertation consists of five chapters written in the journal article style. Chapter One includes this general introduction. Chapter Two consists of a literature review. Chapters Three, and Four are written as stand-alone papers, although for the purpose of this dissertation, figures and tables are shared between chapters. Chapter Three of this dissertation will present estimates of total suspended sediment (TSS) flux measured at Ugly Shack Bayou during both calm weather and storms in 1995 and 1996. This data will be compared and contrasted to the results of a study of sediment deposition conducted by cooperating researchers at a site on the bottom of

Live Oak Bay near the mouth of Ugly Shack Bayou. The two data sets provide a picture of the interactions between bay bottom and bayou sediments and their reactions to controlling factors such as storms and tides. Also included in Chapter Three is a more detailed examination of sediment fluxes in Ugly Shack Bayou and an annual sediment budget for the bayou and the surrounding marsh. Various controlling influences on sediment flux are examined, and storms, tidal currents, seasonal fluctuations in water levels and other factors are shown to influence the flux of suspended sediments. The bayou is a net importer of suspended sediments, indicating that marsh accretion is an active process at Ugly Shack Bayou as it is in other parts of South Louisiana.

Chapter Four presents the results of a study of porewater export from the salt marshes adjacent to Ugly Shack Bayou to open waters that was conducted between April 1996 and April 1997. Although unusual weather patterns disrupted data collection efforts associated with the porewater export study, the data sets that are available provide an opportunity for preliminary evaluation of porewater and discharge characteristics, and the identification of several hydrologic pathways for porewater discharge. Surface runoff and subsurface flow are identified as processes that contribute to porewater discharge, and several techniques are presented for the identification of the origins of water leaving the marsh during low tide exposure of the marsh surface.

CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

This brief literature review is intended to supplement the considerable discussion of the scientific literature that is incorporated into subsequent chapters. The main topics that will be addressed below include sedimentation and land loss in Louisiana coastal marshes, suspended sediment flux in tidal channels, and export of porewater from tidal marshes.

Sedimentation and Land Loss in Louisiana Coastal Marshes

Louisiana contains extensive coastal wetlands which comprise over 40% of the coastal wetlands in the continental United States (Mitsch and Gosselink 1993); Louisiana is experiencing 80% of the wetland loss in the United States (Penland et al. 1990). In recent decades, Louisiana's coastal wetlands are disappearing at a rate of up to 102 km^2 $year^{-1}$ in the Mississippi River deltaic plain (Gagliano et al. 1981), and an additional 26 km^2 yr^{-1} in the Chenier Plain (DeLaune et al. 1983). Modeling studies indicate that the long term stability of Barataria Basin marshes is uncertain (Chmura et al. 1992). The rapid loss and the recognition of the economic importance of the wetlands has led to considerable scientific effort aimed at explaining the reasons for land loss and the mechanisms of sediment dynamics that control land loss processes in marshes and estuaries.

Coastal Louisiana was formed in the recent geologic past by the Mississippi River. The river has changed course approximately every 1000 to 2000 years (Salinas et al. 1986) resulting in a series of overlapping deltas that contain large expanses of flat lands near sea level. The Barataria Basin, located between the current Mississippi

River and its most recently abandoned distributary, Bayou Lafource, is the youngest interfluvial basin in the Mississippi River deltaic plain (Hatton et al. 1983). The low-lying lands of the Mississippi River deltaic plain consist of tidal marshes near the Gulf of Mexico that display a strong zonation in plant species distribution due to the spatial variation in salinities created by saline Gulf of Mexico water mixing with freshwater of the upper estuary (DeLaune et al. 1991). The main ecosystems in Barataria Basin, listed in order of increasing salinity, are swamp forest at the northern limits of the basin, fresh marsh, intermediate marsh, brackish marsh, and salt marsh at the southern end of the basin. The several marsh types are distinguished by salinity as well as by the presence of distinct plant communities (Conner and Day 1987).

The discussion that follows outlines the important factors influencing the disappearance of coastal marsh land in Louisiana. Several related concepts will be introduced and to avoid confusion, their definitions, as they are commonly used in the scientific literature, are included in Table 1.

Baumann et al. (1984) recognized that the survival of marshes depends on a balance between accretion and relative sea level rise. The coast of Louisiana is experiencing relative sea level rise of approximately 0.76 cm yr^{-1} on average. Rates of relative sea level rise are greatest in areas of active deltas and where underlying sediment strata are thickest, and lowest in older deposits and where underlying sediments strata are thin (DeLaune et al. 1991). The large number of studies that have been conducted have resulted in a variety of estimates of relative sea level rise.

Table 1. Definitions of Terms Related to Coastal Land Loss

Term (synonyms)	Definition
eustatic sea level rise	increase in sea level relative to a constant datum due to an increase in the volume of water in the oceans or a decrease in the volume of the ocean basins
subsidence	decrease in the elevation of land surface relative to a constant datum due to compaction of sediments and warping of earth's crust by the weight of sediments
relative sea level rise	the increase in sea level relative to a point on the coast. Relative sea level rise is the sum of eustatic sea level rise and subsidence
accretion (sedimentation)	build up of marsh soils by accumulation of mineral and organic sediments
submergence (accretion deficit)	the lowering of marsh surface level relative to apparent sea level; the difference between accretion and relative sea level rise
land loss	the disappearance of land due to submergence, erosion, or destruction by canal construction

Reported rates of relative sea level rise in the Barataria Basin (cm yr^{-1}) include: 1.83 at Grand Isle; 0.31 at Lafitte; 0.35 at Barataria; 1.45 at Leeville; 1.16 at Des Allemands (DeLaune et al. 1992). Penland et al. (1986) reported rates of relative sea level rise throughout the northern Gulf of Mexico coast. Reported rates from locations outside of Louisiana range from 0.62 cm yr^{-1} at Galveston, Texas to 0.10 cm yr^{-1} at Key West, Florida. The Barataria Basin is experiencing the highest rates of relative sea level rise on the Gulf Coast. Relative sea level rise includes the effects of both eustatic sea level rise and coastal subsidence (DeLaune et al. 1990). Estimated eustatic sea level rise in the Gulf of Mexico is approximately 0.23 cm yr^{-1} (Barnett 1984). However, Madden et al. (1988) estimate that only 2 to 4% of relative sea level rise in Barataria Basin could be attributed to eustatic sea level rise. Relative sea level rise in the Barataria Basin ranges from 0.6 to 0.8 cm yr^{-1} in the upper basin to 1.0-1.6 cm yr^{-1} near the coast (DeLaune et al. 1990). Thus Barataria Basin is experiencing rates of relative sea level rise several times as great as eustatic sea level rise. The difference between relative sea level rise and eustatic sea level rise represents the contribution of subsidence to relative sea level rise, and based on the above data is approximately 0.4 to 0.6 cm yr^{-1} in the upper Barataria Basin and 0.8 to 1.4 cm yr^{-1} in the lower basin. The high rates of subsidence in Barataria Basin results from local compaction and regional subsidence of the Holocene sediments upon which the Basin rests (Salinas et al. 1986).

Sediment accretion on the surface of Louisiana's tidal marshes has been studied extensively. Beginning with DeLaune et al. (1978) numerous researchers have utilized ^{137}Cs dating techniques to measure the rate of sediment accretion in tidal marshes (Hatton et al. 1983; Baumann et al. 1984; DeLaune et al. 1986; DeLaune et al. 1989; Nyman et al. 1990; Nyman et al. 1993b; DeLaune et al. 1992). ^{137}Cs is an isotope that results from atmospheric nuclear weapons testing and does not occur naturally. Significant ^{137}Cs fallout first appeared in 1954 with peak fallout during 1963. As airborne cesium reaches the ground or water it is quickly and permanently adsorbed by clay particles, which are subsequently deposited on marsh or bay bottom surfaces. Thus a soil profile in an area of active accretion, such as a tidal marsh, will show a point of initial ^{137}Cs activity corresponding to the surface in 1954, and a point of peak ^{137}Cs activity corresponding to the surface in 1963. ^{137}Cs is detected in soils and sediments by gamma ray detection. By measuring the depth of the initial and peak ^{137}Cs activities in a sample, the depth of accretion since 1954 and 1963 can be found (DeLaune et al. 1978; DeLaune et al. 1989). ^{210}Pb is a naturally occurring radioisotope that is deposited in a similar manner to ^{137}Cs. ^{210}Pb dating yields deposition rates over the past 80 to 100 years, and has been utilized by several researchers (DeLaune et al. 1989). Other studies have utilized artificial marker horizons placed on the marsh surface to measure accretion. The marker horizon is placed on the marsh surface and cores are collected at seasonal or annual intervals to determine the depth of sediment accreted above the horizon (Baumann et al. 1984; Rejmanek et al. 1988). A similar technique involves the placement of filter papers or petri dishes on the marsh. These objects collect sediments which are then weighed to determine areal sediment deposition rates over periods of one to several weeks (Reed 1989; Boumans and Day 1994). Only a few studies in Louisiana have attempted to measure sediment movement to marshes as it occurs (Boumans and Day 1994; Wang et al. 1993; Stern et al. 1986).

Sediment accretion is an active process in all Louisiana marshes that have been studied. Long-term accretion rates average 0.7 to 0.8 cm yr^{-1} in coastal Louisiana (DeLaune et al. 1992), while in the Barataria Basin rates range from about 1.3 cm yr^{-1} in streamside marshes to 0.7 cm yr^{-1} in backmarshes (Hatton et al. 1983).

DeLaune et al. (1991) report accretion rates averaging 0.84 cm yr^{-1} in Barataria Basin. Thus Barataria Basin marshes are accreting faster than the Louisiana coastwide average. Hatton et al. (1983) report that Louisiana marshes are accreting faster than the average Atlantic seaboard marsh.

Although Louisiana marshes are rapidly accreting sediments, they are not keeping pace with relative sea level rise. DeLaune et al. (1991) report that most regions of the Louisiana coast are currently experiencing coastal submergence, which is the difference between accretion and relative sea level rise. Barataria Basin has among the highest rates of submergence in Louisiana, and is experiencing the highest rate of wetland loss. This submergence is attributed to high rates of relative sea level rise, rather than low rates of accretion. Land loss is attributed to a variety of factors including submergence and increases in salinity (DeLaune et al. 1991).

Submergence of coastal lands creates a variety of changes which ultimately result in the deterioration and disappearance of coastal marshes (Salinas et al. 1986). Accumulation of organic matter, accumulation of mineral sediments, vertical marsh accretion and the continued survival of marshes are all interdependent in coastal Louisiana, and a number of feedback relationships have been identified. Saltwater intrusion into brackish or freshwater marshes or freshwater swamps vegetated by woody shrubs and trees results in reductions in the overall health of vegetation and slower accumulation of carbon and sediments (Pezeshki et al. 1989). Increased flooding of vegetated marshes frequently accompanies salt water intrusion as marsh surface elevation fails to keep pace with relative sea level rise (Salinas et al. 1986).

This flooding is an additional source of stress to vegetation and causes similar responses in vegetation (DeLaune and Smith 1984; Salinas et al. 1986). Vegetation stress is linked to deterioration of marshes and their conversion to open waters (Nyman et al. 1993a). Accumulation of organic matter plays an important role in soil development and vertical accretion in fresh areas of the basin (Kosters et al. 1987; Chmura et al. 1992), as well as in salt marsh areas (DeLaune et al. 1986; Nyman et al. 1993b), so any reduction in the rate of accumulation of organic matter would result in a reduction in overall rates of accretion. Thus, salt water intrusion and increased flooding result in vegetation dieoff and reduced accumulation of organic matter. Both of these effects contribute to marsh deterioration, conversion to open water, and additional salt water intrusion and flooding, resulting in a positive feedback loop that amplifies the effects of saltwater intrusion and flooding of marshes (Nyman et al. 1993b).

A feedback loop that acts in opposition to the saltwater intrusion cycle described above also has been identified. Inundation of marsh surfaces is closely tied to sediment deposition; sediments can reach the marsh surface only when it is flooded (Reed 1989; Baumann et al. 1984). As marsh surfaces fail to keep pace with relative sea level rise and inundation becomes more frequent, sediment deposition rates are expected to increase (DeLaune and Smith 1984; Nyman et al. 1993b). The high rates of accretion in Barataria Basin are thought to be due to high rates of coastal submergence, which keeps accreting marsh surfaces at an elevation where they are frequently inundated and therefore receive large inputs of sediments (Hatton et al. 1983).

Constant inputs of sediments are vital for the survival of salt marshes both as a contributor to the vertical accretion needed to maintain marsh elevation above rising relative sea level (Baumann et al. 1984) and to support healthy vegetation. Sediment inputs to salt marshes increase plant productivity and reduce plant stress (DeLaune et al. 1993) as well as provide trace minerals important in sulfide immobilization in salt marshes (Feijtel et al. 1989). Thus, by increasing plant productivity, mineral sediment accumulation plays an important role in the accumulation of organic matter, which magnifies the effects of the mineral sediments in increasing vertical accretion (Nyman et al. 1993b). The largest accumulations of organic matter are associated with relatively large amounts of mineral sediments (Kosters et al. 1987), and the relationship between mineral sediment input, increased vegetation productivity, and increased organic deposition has been suggested as an important mechanism in natural levee growth (Rejmanek et al. 1988). Increased plant productivity and the resultant increased standing plant biomass has been correlated with increased sediment deposition, creating another feedback mechanism enhancing marsh accretion (Rejmanek et al. 1988).

In non-riverine estuaries like the Barataria Basin, mineral sediment inputs are greatest in coastal salt marshes and decrease inland, with the lowest rates of deposition occurring in fresh marshes. However, salt marshes require almost twice as much mineral matter to accrete a given increment of soil as do fresh marshes

(Nyman et al. 1990). This offsets the advantage of additional mineral sediment inputs to salt marshes and allows fresh marsh soils to accrete without high mineral sediment inputs (Nyman et al. 1990; Hatton et al. 1983). However, the relatively small inputs of mineral sediments that fresh and brackish marshes do receive are important in the formation of marsh soils, which are currently accreting at a rate near the rate of relative sea level rise in the upper Barataria Basin (DeLaune and Smith 1984).

Natural sediment deposition in sediment-poor estuarine marshes such as those in the Barataria Basin is controlled mainly by storms. Both extra-tropical winter storms and tropical storms including hurricanes can have important effects on sediment deposition in marshes (Baumann et al. 1984; Reed 1989). The chance of a hurricane passing within 80 km of a site in the Barataria Basin is 12% annually (Baumann et al. 1984), despite this low frequency of occurrence, the intensity of hurricanes makes their potential impacts large. Rejmanek et al. (1988) found that a minor hurricane deposited as much sediment as more than 20 years of typical, non-storm conditions in a marsh in Terrebone Parish, Louisiana. Similarly Baumann et al. (1984) found that a hurricane and a tropical storm during one summer deposited approximately 2/3 as much sediment as was deposited over the remainder of their 4 1/2 year study of Barataria Bay marshes.

The passage of cold fronts through coastal Louisiana occurs approximately 30 times each winter between October and April (Moeller et al. 1993); their large spatial scale ensures that most cold fronts will influence the entire Louisiana coast. Therefore, cold fronts are believed to have larger cumulative impacts on coastal regions than the more powerful but less frequent hurricanes (Roberts et al. 1987). A similar situation has been discovered in other Gulf Coastal locations (Leonard et al. 1995). Cold front passages on the Gulf Coast produce a consistent sequence of winds, waves, air pressure, and water level fluctuations, and these repeated effects have a distinctive cumulative impact on the Louisiana coast (Moeller et al. 1993; Huh et al. 1991; Roberts et al. 1987). The impacts of cold fronts include suspension and transport of bay bottom sediments (Roberts et al. 1987; Leonard et al. 1995), and a sequence of rising, then falling, water levels in coastal embayments that floods tidal marshes and results in sediment deposition (Reed 1989; Baumann et al. 1984).

Anthropomorphic disturbances to coastal marshes also have a significant impact on accretion and survival of Louisiana coastal marshes. The most widespread and probably the most significant impact of human development on Barataria Basin marshes has been the levying of the Mississippi River and the damming of Mississippi River water flow into Bayou Lafource. These two channels form the eastern and western boundaries of the Barataria Basin, respectively, and formerly supplied large inputs of sediments to the basin during the annual spring flood of the Mississippi. Bayou Lafource was cut off from Mississippi River flow in 1904 (Nyman et al. 1993b), and the entire Mississippi River has been leveed since the 1940s (Conner and Day 1987). Since the levying of the Mississippi, riverine sediment is no longer available to intertidal marshes; this constitutes a primary cause of the loss of Barataria Bay wetlands (Salinas et al. 1986; DeLaune et al. 1992; DeLaune et al. 1978). Scientists estimate that less than 10% of the annual sediment load of the Mississippi River, if it could be distributed to coastal marshes in Louisiana, would increase marsh accretion enough to keep pace with relative sea level rise (DeLaune et al. 1992).

The other type of human impacts on coastal marshes is the construction of canals, artificial levees, and water control structures such as weirs. Some of these disturbances (canals, levees) are the byproduct of oil and gas exploration, while others (weirs) are deliberately constructed and meant to enhance a certain use of marshes, such as waterfowl wintering habitat or furbearer production, or to reduce salt water intrusion into marshes in hopes that this will combat land loss in the marsh (Boumans and Day 1994). Although canal construction is widely believed to lead to accelerating land loss, Hatton et al. (1983) and DeLaune et al. (1989) found that vertical accretion of marsh sediments was not significantly affected by the proximity of a man-made canal. They suggested that the more significant impact of canal construction could be an increase in water level due to the presence of the canal. This could result in vegetation stress and lead to the deterioration of marshes near canals. Weirs, on the other hand, reduce both water flow and sediment accretion in affected marshes and thus may increase rather than decrease marsh deterioration (Boumans and Day 1994).

<u>Suspended Sediment Flux Through Tidal Channels</u>

Although coastal marshes are sediment sinks over long time scales, as is evidenced by the thick sedimentary sequences which underlie most marshes, studies of sediment flux indicate that most marshes studied are presently losing sediments

(Stevenson et al. 1988). The majority of studies of tidal sediment flux in marsh channels have been conducted on the United States Atlantic Coast, where high salinity marshes are losing 1 to 2 kg sediment m^{-2} yr^{-1}. Submerged upland marshes on Chesapeake Bay are losing as much as 14 kg sediment m^{-2} yr^{-1}.

Several studies have investigated the hydrodynamic characteristics of the flows in tidal creeks, but most researchers have concentrated on the hydrodynamics of tidal channels on coastlines where tidal ranges are at least 2 to 3 m, and their results may not be applicable to conditions in a microtidal environment like Louisiana, where tidal range is typically about 30 cm. Reed (1987) examined the velocity characteristics of tidal flows in a macrotidal (tide range = 2.5 m) English salt marsh and discovered that significant velocity pulses occurred during both flood and ebb tides. These short-duration changes in velocity resulted in significant undermeasurement of tidal volume when flow integration was at 30 min intervals as compared to volumes obtained by integrating at 5 min intervals. Reed allowed, however, that velocity pulses are unlikely in microtidal marshes where velocities are much lower than at her study site. Healey et al. (1981) examined the causes of velocity pulses and discovered that they may be related to non-zero water surface slopes in tidal channels which developed in their macrotidal marsh in Norfolk, England. The neap tide range in this marsh is 2 to 3 m, spring tide range is 5 to 6 m (Bayliss-Smith et al. 1979). Bayliss-Smith et al. (1979) found, in the same marsh creek, that current velocity regime during a tide was related to the position of the water surface relative to the marsh surface. The greatest tidal flows were generated by tides that overtopped the marsh surface allowing greater tidal prism volume in the creek. French and Stoddart (1992) examined tidal flows in Norfolk, England and determined that marsh morphology is controlled both by typical, below bank tide and the occasional stronger over-bank tide. Their study found that sediment concentration is closely tied to tidal stage, with the highest concentrations of suspended sediments occurring during over-bank tides. The lone study of the hydrodynamics of a tidal creek in a microtidal marsh was conducted in the Terrebonne Bay Estuary of Louisiana (Wang et al. 1994). That study revealed that man-made channels connecting with the mid-reaches of a tidal bayou have resulted in flow patterns in the bayou different from the pattern expected for a natural bayou. The interception of tidal flow by man-made channels has caused sedimentation in the upper reaches of the bayou, illustrating the tendency of Louisiana marsh environments to accrete sediment.

Several researchers have examined the accuracy of accepted methods of calculating sediment flux in tidal channels. Pillay et al. (1992) estimated sediment transport rates in a South Carolina tidal channel using three methods. The first method integrated velocity, subsectional area, and suspended sediment concentration for each of several subareas of the cross section of the creek. This method was considered to represent the true discharge in the creek. The second method utilized areally averaged velocities and suspended sediment concentration in treating the entire creek cross section as a single unit, while the third used measurements of velocity and suspended sediment concentration at a single point in the creek to represent conditions throughout the creek cross section. The study revealed that both the second and third methods of calculating sediment discharge yielded a value that under some conditions differed from, but that was highly correlated with the true sediment discharge. Similarly Roman (1984) estimated water volume discharge through a tidal creek using a dense array of current meters and compared the results with estimates of water volume discharge based on a single current meter. This study revealed that a single current meter yielded water volume discharge estimates with 11% of instantaneous discharges and 7% of total tidal cycle discharge, thus supporting the notion that a simplified array of velocity meters can produce acceptable estimates of water volume discharge. Boon (1978) studied sediment flux in a tidal channel and estimated that instantaneous estimates of flux using a dense array of current meters include an error of approximately 7%, and integrated flood or ebb tidal flux estimates that include a 7 to 10% error. In a study of sediment and water discharge through a tidal creek in South Carolina, Ward (1981) utilized a total of 6 current meters at three points in the creek cross section, and estimated that error of 10 to 15% was associated with estimates of sediment flux. The author reasoned that residual flux for a tidal cycle must therefore exceed 15% of the average gross flood and ebb flow to be considered significant. Leonard et al. (1995) published the only study of tidal sediment flux in a microtidal environment. Their results indicate that error of approximately 16% is associated with sediment flux calculated using measurements at a single station as compared to the values obtained using an array of 21 velocity measurements and numerous (6) measurements of suspended sediment.

Ward (1981) monitored suspended sediment flux in a marsh tidal channel at Kiawah Island, South Carolina during March and July/August. Most export was in a seaward direction during both seasons sampled, with the exception of a net balance of inorganic materials during the March sampling period. Higher concentrations during summer than winter were attributed to increased thunderstorm activity and bioturbation during the summer, while the general tendency for material export was attributed to time/velocity asymmetry of tidal currents; stronger ebb than flood currents carry more material seaward than is carried inland. Time/velocity asymmetry of tidal currents was also cited by Leonard et al. (1995) as playing an important role in controlling sediment flux in a Florida tidal creek. Although net sediment transport was typically small during fair weather, slight net ebb transports of sediments were attributed to higher ebb than flood currents in the creek. Jordan et al. (1986) examined the sediment budget of a tidal marsh in Maryland and found that tidal sediment exchange was not related to rainfall. Accumulation of sediments on the marsh surface was directly related to the amount of time the marsh surface was inundated by tidal waters. Settlemeyer and Gardner (1977) examined sediment transport through a tidal creek in Charleston Harbor, South Carolina. Their result indicated that total and organic suspended solids are exported during summer and approximately in balance during the winter. Stevenson et al. (1985) examined a deteriorating marsh in Maryland and discovered that despite periodically high concentrations of sediments in adjacent channels, little sediment was able to reach interior areas of the marsh. A large net export of sediments was related to the general sediment deprivation of the marsh surface and its incipient deterioration.

Storms have been cited by many researchers as playing an important role in controlling suspended sediment flux. Ward (1981) found that high winds and heavy rains caused the highest concentrations of suspended sediments at his study site. Similarly Leonard et al. (1995) found that storms resulted in the highest concentrations of sediments in an open marine creek, but that large tidal prisms, whether astronomical or storm tides, coinciding with storms were necessary to cause large imports of sediments. Storm-driven fluxes were found to play an important role in the sediment budget of the marsh. Settlemeyer and Gardner (1977) found high suspended sediment concentrations occurred at any time of year when wind conditions were favorable. Stevenson et al. (1985) found that storms resulted in deterioration of their Maryland marsh due to enlargement of incipient ponds by storm winds.

Marsh Porewater Export

Although numerous studies have included measurements of the chemical characteristics of marsh porewaters, relatively few studies have examined porewater movements or porewater exports from tidal marshes. Several researchers have examined seepage of porewaters out of marsh substrates during low tide exposure. Wolaver et al. (1986) found that the highest concentrations of dissolved organic carbon (DOC) in a South Carolina tidal creek occurred at low tide, and attributed this to seepage and runoff from tidal marshes, where porewater and seepage was found to contain high concentrations of DOC. An additional study (Wolaver and Spurrier 1988) demonstrated that runoff and seepage from the marsh resulted in a significant annual export of DOC.

Gardner (1975) examined the runoff from a number of small marsh creeks during tidal exposure of a South Carolina marsh and found that such runoff resulted in significant export of several constituents of marsh porewater. Silica export from the marsh was extrapolated to the entire South Carolina coast and was found, on an annual basis, to be comparable to silica export from South Carolina rivers. Whiting et al. (1989) examined a similar creek in South Carolina and found that runoff during tidal exposure resulted in substantial exports of organic nitrogen from the marsh. Jordan and Correll (1985) estimated porewater seepage from a Maryland marsh based on water table fluctuations and marsh soil hydraulic conductivity, and found that seepage could account for a substantial part of the export of nutrients observed in the marsh. Yelverton and Hackney (1986) estimated porewater seepage using similar methods and estimated that the majority of porewater export occurred from the portion of the marsh within 2 m of a tidal creek. As a result of this narrow zone of exchange, relatively little export of DOC occurred from the marsh on an areal basis. Agosta (1985) found that porewater export from a South Carolina marsh occurred from within 4 m of the creekbank, and this water was replaced by porewater from more interior areas of the marsh, a process which resulted in imports of nutrients from interior marsh areas to streamside marshes. Harvey et al. (1987) modeled, and measured in the field, porewater export from a 20 m wide salt marsh in Virginia, and found that considerable export of porewater occurred during each tidal cycle. They estimated that a zone of influence of approximately 15 m, or most of the marsh width, was responsible for porewater export. Their model suggested that marsh elevation relative to water levels has a greater influence on porewater export than is exerted by soil properties. Nuttle (1988) modeled porewater movement in a New England salt marsh and found that most horizontal movement of porewater occurs within 2.5 m of the creek and that more than 15 m from the creek there is little or no horizontal movement of porewater. The zone between 2.5 and 15 m from the creek bank is subject to alternating periods of horizontal movement and no horizontal movement due to variations in tidal flooding of the marsh surface. These results are supported by the earlier work of Hemond and Fifield (1982) who examined porewater movement at a point 15 m from a tidal creek in Great Sippewissett Marsh in Massachusetts. Their study verified that little horizontal porewater flow occurred at their site, although they suggested that conditions would be different nearer the creek bank.

CONCLUSIONS

The literature review here reveals that several research needs exist in Louisiana's coastal marshes. Ongoing coastal land loss has been attributed to a difference between relative sea level rise and marsh sediment accretion. Although marsh sediment accretion has been tied to sediment movement between coastal water bodies and adjacent marshes, little research has directly examined the movement of sediments between open waters and marshes or the relationships between sediment dynamics in open waters and in marshes. For this reason, sediment flux in a salt marsh bayou has been studied here. The relationships between sediment flux in the bayou and sediment dynamics in the adjacent bay will be discussed in Chapter Two, while Chapter Three will present an annual sediment budget for the bayou and will discuss factors influencing the magnitude and direction of sediment fluxes. Another research need identified here is the need for an examination of the export of porewaters from coastal marshes to estuarine waters. Louisiana contains both the largest coastal marshes and the richest coastal fisheries in the contiguous United States. While a connection between marshes and high productivity of nearby open waters has frequently been discussed, little research, and no research conducted in Louisiana, has addressed the export of porewater or porewater constituents from marshes to open waters. Such export represents a potential pathway for nutrient and energy exchange between marshes and estuarine waters, and its quantification would add greatly to the current understanding of material balances in marshes and, subsequently, estuarine ecology. Chapter Four presents research which begins to quantify porewater exports from tidal marshes.

CHAPTER 3. SEDIMENT DYNAMICS IN AN ESTUARINE EMBAYMENT, TIDAL BAYOU, AND TIDAL SALT MARSH IN SOUTHEASTERN LOUISIANA, U.S.A.

INTRODUCTION

The state of Louisiana, situated at the mouth of the Mississippi River along the northern coast of the Gulf of Mexico, contains approximately 3.0 million ha of coastal marshes and estuaries, of which 1.4 million ha are coastal marshes. This amounts to approximately 40% of the total coastal marsh area of the contiguous United States (Day et al. 1973; Mitsch and Gosselink 1993). These wetlands and estuaries are both ecologically and economically important, providing wintering grounds for migratory birds, nursery grounds for marine and estuarine fish and shellfish, and a base for oil and gas extraction from underlying deposits.

The stability of coastal wetlands in Louisiana is dependent upon the deposition of sediments carried in by flood waters associated with tidal or weather driven inundation of the wetlands (DeLaune et al. 1983; Baumann et al. 1984; Reed 1989). While the majority of research over the last four decades has shown that Louisiana marshes are accreting sediments, Louisiana's coastal wetlands are at the same time rapidly disappearing. Wetland disappearance can be directly linked to various processes including eustatic sea level rise, compaction of geologically young sediments, plant dieoff due to submergence and salt-water intrusion, and the sediment deprivation of certain areas due to channelization and levying of the Mississippi River system. In order for the coastal wetlands to persist, the rate of accretion of new sediment must exceed the rates of eustatic sea level rise and compaction of underlying sediments (Baumann et al. 1984). Thus, the continued existence of coastal wetlands is closely tied to estuarine/wetland sediment dynamics.

Scientists generally agree that the source of sediments delivered to marshes in non-riverine estuaries of Louisiana, like the Barataria Estuary, is open water bodies adjacent to the marshes (Reed 1989; Baumann et al. 1984). Therefore a study such as this one, which examines sediment dynamics in both a shallow estuarine bay and a tidal bayou/marsh system, has the potential to identify important relationships between the sediment dynamics of the two areas studied and to define the interdependence of the two systems.

The Barataria Basin was formed as an interdistributary basin between the present course of the Mississippi River, which borders the basin to the east, and Bayou Lafource, the most recently abandoned distributary of the Mississippi, which borders the basin to the west. Prior to European settlement of Louisiana, the Barataria received substantial inputs of sediments and fresh waters from the Mississippi River during periods of high river flow. However, Bayou Lafource has been disconnected from substantial Mississippi River influence since 1902 and the main channel of the Mississippi has been leveed since the 1940s, resulting in the elimination of the sediment supply to the Barataria. This has resulted in ongoing land loss in the Barataria Basin as the result of relative sea level rise in excess of sediment accretion in tidal marshes (Conner and Day 1987).

Practically all published studies of marsh sedimentation in Louisiana have reached the same conclusion; marsh surfaces in Louisiana, including those in regions where marshes are actively degrading, are currently accreting sediment (Hatton et al. 1983; Baumann et al. 1984; Delaune and Smith 1984; Delaune 1986; Delaune et al. 1986; Kosters et al. 1987; Delaune et al. 1989; Reed 1989; Delaune et al. 1990; Nyman et al. 1993b; Wang et al. 1993; Boumans and Day 1994). This universal accretion would appear to insure that tidal marshes in Louisiana act as sediment sinks, removing sediments from estuarine waters.

Stevenson et al. (1988), however, demonstrated that most tidal marshes in the United States are currently losing sediment at rates as high as 14 kg m^{-2} yr^{-1} based on measurements of suspended sediment flux in tidal channels. This disparity may be due to recent changes in sediment availability or to the undermeasurement of the effects of major storms on sediment budgets (Stevenson et al. 1988), or the variability in the rate and direction of net sediment flux between marshes. Another potential explanation for this disparity may be the difference in the processes being examined by coring or marker horizon techniques as compared with measuring suspended sediment flux in channels.

Long-term measurements of marsh sedimentation in Louisiana have been made using cores of marsh sediments obtained from the vegetated marsh surface. By examining the depth of sediment present over an identifiable horizon, average sediment deposition over the last several decades can be determined (Hatton et al. 1983; Baumann et al. 1984; DeLaune and Smith 1984; DeLaune 1986; Delaune et al. 1986; Rejmanek et al. 1988; DeLaune et al. 1989; Nyman et al. 1993b). Shorter term measurements have quantified deposition of sediments above artificial marker horizons or on filter papers placed on the vegetated marsh surface. These studies measure seasonal or annual sedimentation rates (Rejmanek et al. 1988; Reed 1989; Boumans and Day 1994). Both of these methods, which represent the majority of sedimentation measurements made in Louisiana, consider only the vegetated surfaces of tidal marshes and do not account for processes taking place in tidal channels, mud flats, or ponds, which constitute a substantial portion of marsh areas.

Another weakness of existing measurements of marsh sedimentation in Louisiana is that the techniques employed measure at a coarse time scale (decadal or seasonal time scales). Measurement of tidal flux of suspended sediments measures sediment movement as it occurs and permits the identification of individual events that result in sediment transport as well as comparison of sediment flux with simultaneously measured controlling factors such as velocity and direction of tidal water currents, water level fluctuations, wind speed and direction, and rainfall.

Measurements of suspended sediment flux through tidal channels have been employed in many locations in the United States, but have not been widely used in Louisiana. Boumans and Day (1994) examined the impacts of two marsh management plans on suspended sediment fluxes in tidal channels at two locations in coastal Louisiana. Their studies included measurements at three times during the year, and revealed that managed marshes where water exchange is controlled by weirs receive considerably less sediment than unmanaged marshes. Stern et al. (1986) studied sediment and water flux through a bayou connecting a tributary of the Atchafalaya River with Fourleague Bay. They determined that bayou flow and sediment flux is frequently dominated by Atchafalaya River discharge. Wang et al. (1993) examined suspended sediment concentrations along a transect running from a tidal bayou into a salt marsh near Terrebonne Bay, an area hydrologically and sedimentologically similar to Barataria Bay. Their study found that, under normal tidal conditions, net sediment transport is from the bayou toward the marsh interior, but did not study the effects of storms on sediment dynamics.

Measuring the flux of sediments through a tidal channel integrates processes occurring on the vegetated marsh surface with processes occurring in mud flats, ponds, and within the channel itself; sediment flux is a function of sedimentation in all parts of the marsh environment. No thorough study of tidal sediment flux that encompasses a substantial portion of the annual seasonal variability in Louisiana marshes has been published. Such a study has the potential to quantify the net sediment balance of the entire marsh system rather than focusing narrowly on vegetated surfaces, and can potentially identify important erosional processes occurring in tidal marshes which cannot be examined by coring or marker horizon techniques. Furthermore, although storms are widely believed to exert a strong influence on sediment dynamics in Louisiana, few studies have examined sediment dynamics during storm events.

As part of a larger study of the sediment and carbon dynamics of Louisiana's Barataria Bay Basin funded through NASA's EPSCoR program, we examined sediment flux through a small, tidal bayou (Ugly Shack Bayou) that hydrologically connects inland portions of the bayou and intertidal salt marsh with the adjacent bay

(Live Oak Bay). Flux rates of sediments between Live Oak Bay and intertidal marshes and inland portions of Ugly Shack Bayou were monitored by combining measured water flux rates with suspended sediment concentrations obtained from periodic samples. In addition, suspended sediment concentrations in Live Oak Bay, water level fluctuations, and meteorological variables were monitored during visits to the site for comparison with deposition and flux rates. The results of this study are compared to sediment deposition rates on the bottom of Live Oak Bay examined using the radiochemical tracer ^{7}Be reported in Rovansek et al. (1997); the two data sets provide a picture of the interconnection of sediment dynamics in the bayou/marsh and bay. Sediment fluxes are discussed in terms of controlling factors such as tidal water currents, water level fluctuations, and storms, and an annual sediment budget is completed for the bayou and adjoining marshes.

STUDY AREA

The study site is located in Louisiana's Barataria Estuary near New Orleans (Fig. 1). The center of the site is located at approximately 90 3' 45" west longitude and 29 24' 00" north latitude. The Barataria Estuary occupies an approximately triangular area in southeast Louisiana on the northern coast of the Gulf of Mexico. The total drainage area of the basin is about 628,000 ha, including 202,128 ha of open waters and 206,182 ha of marshes (Conner and Day 1987). The basin is bordered on the east by the levees of the Mississippi and on the west by the levees of Bayou Lafource, the most recently abandoned distributary of the Mississippi. It is thus isolated from freshwater inflows other than precipitation, which averages approximately 160 cm in south Louisiana and is fairly uniformly distributed throughout the year (Baumann 1987). The southern border of the basin is a series of islands and tidal passes to the Gulf of Mexico. The southern end of the estuary is saline, with salinities approaching those of the Gulf. Waters in the northern end of the basin are fresh. Land in the basin is low-lying and generally wet. Land in the northern, freshwater portion of the basin is occupied by cypress/tupelo swamps and freshwater marshes. As conditions become increasingly saline to the south, vegetation grades from freshwater marsh to brackish marsh and finally to salt marsh in the southern portions of the basin.

Open waters of the basin are connected by an intricate system of natural and man-made channels. Tides in Barataria Basin are typically diurnal and of small range; mean tidal range at the coast is approximately 32 cm (Baumann 1987). The study site is fairly near the coast and well exposed to open waters, therefore relatively little attenuation of tidal amplitude should be expected. Conner and Day (1987) report that salt marshes in the Barataria Basin experience one tidal cycle per day averaging 30 cm in amplitude. Open waters of the lower (saline) basin are typically shallow and turbid with muddy substrate (Conner and Day 1987).

The study site, Ugly Shack Bayou, is adjacent to Live Oak Bay, a small embayment on the northeast portion of Barataria Bay, where depths range between 1 and 2 m and bottom sediments are typically fine-grained (silty clay). The marshes surrounding Live Oak Bay are hydraulically connected to the bay by a series of natural tidal bayous. Some of these bayous are now connected to man-made canals while others, including Ugly Shack Bayou , divide into smaller channels and shallow ponds and, at the inland end, eventually disappear into the marsh. Ugly Shack Bayou is approximately 2 m deep and 30 m wide near the bay. Tidal bayous are connected throughout their length to the marsh surface by numerous small rivulets, the largest of which are typically less than 0.5 m deep and 1 to 2 m wide. These rivulets provide a pathway for flooding or draining of most of the marsh surface. The elevation of the marshes at Live Oak Bay is approximately 15 cm above mean sea level; larger bayous such as the lower reaches of Ugly Shack Bayou are bordered by ridges elevated 30 to 40 cm above the level of more inland marshes. Marshes are vegetated mainly by *Spartina alterniflora* (oyster grass), with smaller amounts of *Spartina patens* (saltmarsh cordgrass), *Distichlis spicata* (saltgrass), and *Juncus roemerianus* (black needlerush).

Live Oak Bay was selected for this study because it is a typical embayment in the saline lower reaches of the Barataria estuary and because it receives drainage from several small tidal bayous. Ugly Shack Bayou was chosen for this study because it is undisturbed by canal construction, it drains a portion of the marsh without connection to other bayous or canals, and because it and the marshes it drains are otherwise typical of this part of the Barataria Estuary.

HYDROLOGY AND SEDIMENT DYNAMICS OF THE BARATARIA ESTUARY

This section will provide an overview of the hydrology and sediment dynamics of the entire Barataria Basin based on the findings of the NASA EPSCoR Project "Carbon Cycling and Hydrology in a Shallow Coastal Estuary," of which this study is a part. Results of the larger project are reported in detail by Garrepally (1996) and Denmon (1996). The NASA EPSCoR Project "Carbon Cycling and Hydrology in a Shallow Coastal Estuary" examined a number of related physical processes and characteristics of the Barataria Estuary in coastal southeastern Louisiana. Research that is particularly pertinent here included a study of the spatial and temporal distribution of suspended sediments and other constituents of estuarine waters, and measurements of suspended sediment and water fluxes between upper, freshwater portions of the estuary and Lake Salvador and between Lake Salvador and lower portions of the estuary (Denmon 1996; Garrepally 1996). The suspended sediment and water flux studies listed above produced a description of the annual pattern of water and sediment dynamics in the Barataria Estuary.

The Barataria Basin (Fig. 1) can be separated into the upper basin (above Lake Salvador) which is entirely freshwater, the middle basin (just below the lake to the northern edge of Barataria Bay) which is brackish, and the lower basin, including extensive salt marshes and large saline bays. In addition to the natural connection via Bayou Perot, the Barataria waterway, a dredged channel about 100 m wide and 5 m deep, directly connects the upper basin with Barataria Bay, and appears to be a corridor of water movement between Lake Salvador and Barataria Bay (Denmon 1996). The bimodal distribution of water levels that is evident in the lower basin (Fig. 2) occurs also in the middle and upper basins (Garrepally 1996). This pattern of water level fluctuations and prevailing weather patterns divides the year into three sediment transport seasons: spring runoff (April-July); summer expansion (August -

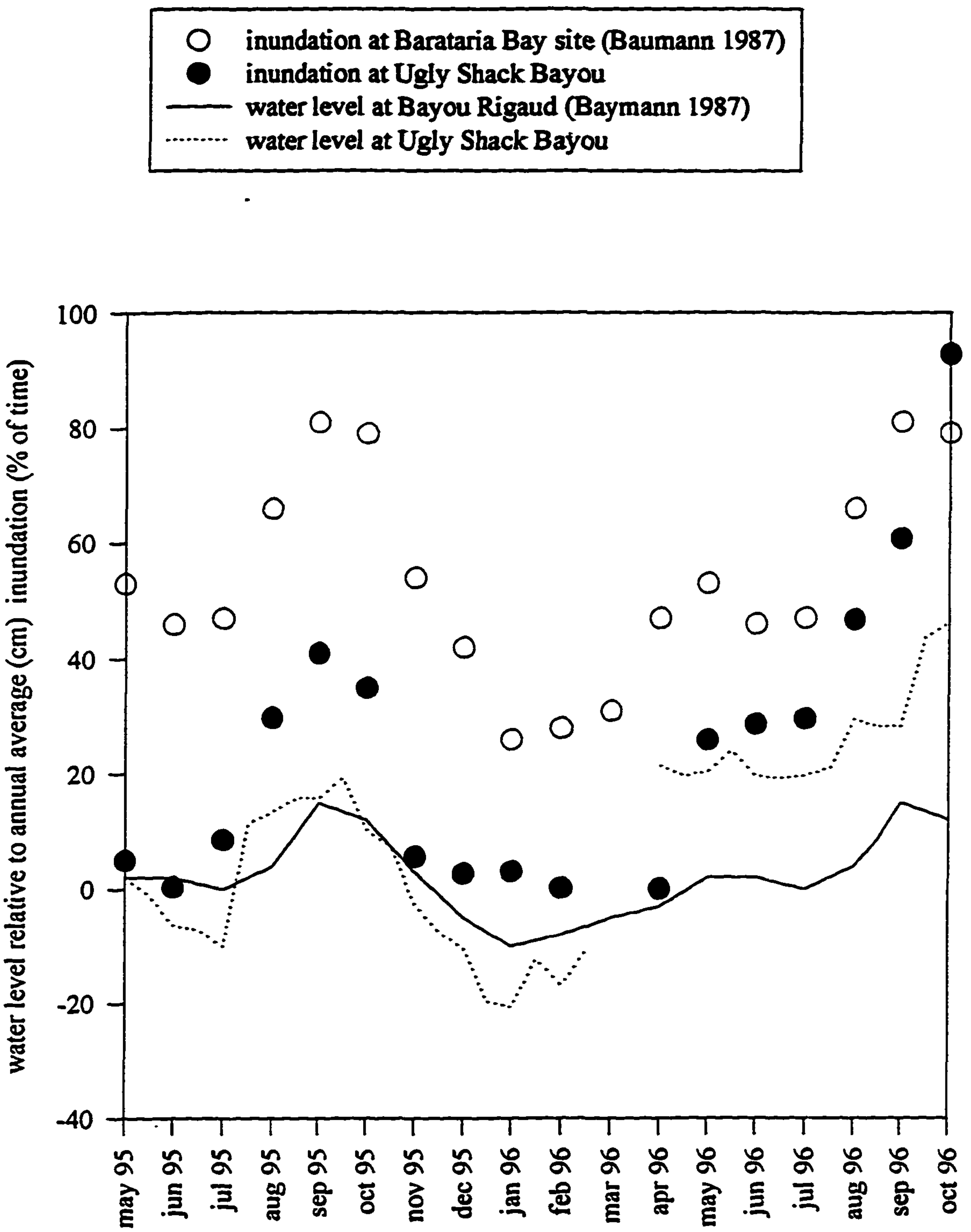


Figure 2. Marsh surface inundation and water level at Ugly Shack Bayou and in Barataria Basin[a].

[a]long-term average data reported by Baumann (1987). Inundation measured near Barataria Bay, water level data are for Bayou Rigaud, near Grand Isle, LA

October); and winter frontal (November - March). These seasons correspond to the three seasons identified later in this chapter based on conditions at the Ugly Shack Bayou study site in the lower basin.

The spring runoff season is a period of downstream transport of water and sediments from the upper basin into and through Lake Salvador to the middle and lower basin (Garrepally 1996). The upper basin produces over 60,000 metric tons of sediment per year (Madden et al. 1988) and much of it is transported into Lake Salvador during the spring runoff season. Significant amounts of this sediment is transported out of Lake Salvador into the middle and lower basin during spring runoff season (Garrepally 1996).

During the summer expansion season, flow direction frequently reverses, with water moving from Lake Salvador into the upper basin due to rising water levels in the gulf (Garrepally 1996). Higher water levels throughout the estuary at this season isolate bottom sediments from disturbance by waves on the surface of the water, and result in lower concentrations of TSS throughout the basin during summer expansion. Thus, little sediment is supplied to the lower basin during the summer months.

The winter frontal season coincides with falling water levels in the basin. High winds and disturbed weather associated with frontal passages result in high concentrations of TSS, and large amounts of sediments are apparently transported from the upper basin to the lower basin during this season (Garrepally 1996).

METHODS

The flux of suspended sediments through Ugly Shack Bayou was estimated by multiplying water flux rates by measured suspended sediment concentrations in the water. Water flux is the product of measured water velocity and bayou cross-sectional area. Water velocity was measured using two electromagnetic current meters mounted on a scaffold platform constructed near the middle of the bayou. A diagram of the platform and current meters is shown in Fig. 3. Current meters were placed in the center of flow at depths of approximately 20 and 80% of the total bayou depth at the measurement point. Average water current velocity at each meter was recorded every 20 min by a datalogger. The average of the two meters' readings was used as the average channel velocity in computing water flux. Channel cross section was computed based on a measured cross section of the bayou and water level measured by a submersible Seabird pressure gage, which recorded average water level at 20 min intervals.

Suspended sediment concentrations in the bayou and in Live Oak Bay were obtained by weighing filter papers through which a known volume of sample was passed. Water samples were collected by ISCO automatic water samplers from approximately mid-depth in the bayou near the current meters at intervals ranging from 1 to 4 hrs. Bay water samples were collected near the water surface by hand from a boat. Measured volumes of sample were filtered in the laboratory onto pre-weighed and pre-rinsed 0.7 micron glass fiber filters. Filters were dried at 105 C to obtain the concentration of total suspended solids (TSS), then fired at 550 C for one

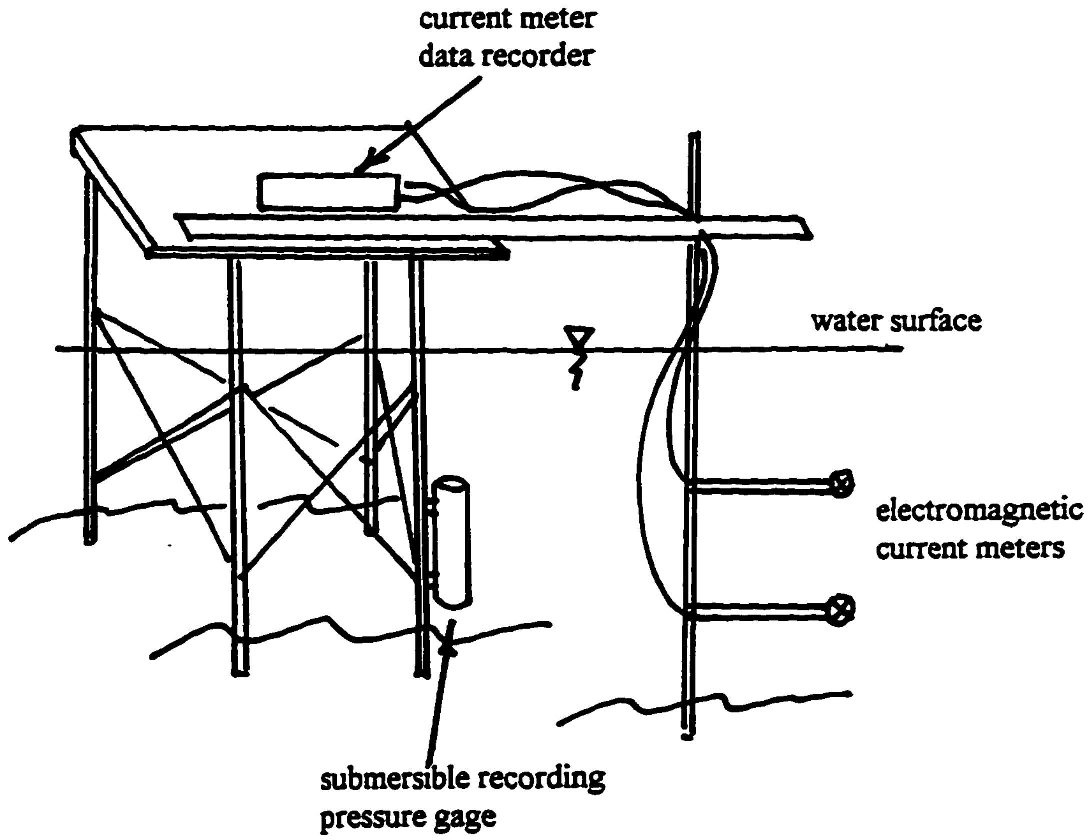


Figure 3. Ugly Shack Bayou instrument platform.

hour to obtain the concentration of volatile suspended solids (VSS). Only a single replicate of each sample was processed. Therefore no estimate of the measurement error associated with our procedure can be made.

Due to the time and effort required to collect and process samples for TSS and VSS, estimation of TSS and VSS flux was possible only during limited intervals of time, ranging in length from two to eight days. Sampling intervals occurred during June 1995, July-August 1995, October 1995, and January-February 1996. Data collection intervals were timed to include as many seasons and weather conditions as possible. Suspended sediments in Live Oak Bay were measured at two stations during each visit to the site. One site was located approximately halfway across the bay adjacent to the mouth of the study bayou, while the other was located near the intersection of Live Oak Bay and larger Hackberry Bay.

The net flux of suspended sediments for a tidal cycle in the bayou was estimated by summing the flood tide (inland) flux and the ebb tide (seaward) flux over a complete tidal cycle (low slack to low slack water or high slack to high slack water). Where possible, the net flux over several consecutive tidal cycles was summed and the total net flux observed was divided by the number of tidal cycles measured. When possible, tidal cycles that were free from major disturbing influences (e.g storm activity) and where net water flux was small (i.e. consecutive low-slack or high slack tides at approximately the same stage level occurred) were chosen to represent typical, non-storm flux conditions in the bayou. During storm events, net flux was calculated over the duration of the event, typically several days.

Flux was summed over an integer number of tidal cycles to eliminate the bias that would be introduced by including fractions of tides. Thus, where the effects of a storm might have lasted 4.5 tidal cycles (5 flood and 4 ebb tides) an additional ebb tide was included in the calculation of net storm-driven flux to reduce or eliminate the effect of net water flux on the calculation of net sediment flux.

Marsh Surface Inundation

Three shallow wells equipped with recording water level gages (Druck 540 water level gages connected to a Campbell CR10x datalogger) were installed in the marsh adjacent to Ugly Shack Bayou during May 1996. These wells are located along a 3.7 m transect beginning in a shallow rivulet and extending toward the marsh interior. The water level records from these gages and the record from the gage in the bayou were used to determine the vertical position of the marsh surface at the wells relative to the bayou gage. A marsh surface survey conducted in May 1996 was used to determine the range of marsh surface elevations that occur at the site. By comparing the records from the water level gages on the marsh with the record of the gage on the bayou, the bayou gage level at which water from the bayou would begin to inundate the marsh was determined. Based on this value, periods of time during which the marsh would be inundated were determined using the bayou water level records.

The drainage area of Ugly Shack Bayou was determined from USGS 1/24,000 series maps of the area. Drainage boundaries were determined based on field observations. The drainage area of Ugly Shack Bayou is approximately 710,000 m^2.

Sediment Erosion from the Marsh Surface During Rainfall

The runoff of sediment from the marsh surface was measured during a thunderstorm that occurred while the marsh surface was exposed by low tide on September 20, 1996. Runoff through a small rivulet on the surface of the marsh was gaged using a handheld Marsh-McBirney electromagnetic current meter, and samples of the water in the rivulet were collected by hand and processed in the same manner as samples from the bayou. Flow in the rivulet was measured and samples were collected every 30 min or more often during the peak rainfall when discharge and TSS were changing rapidly. The measurement of discharge and characteristics of the rivulet are described in more detail in Chapter Four.

Storm Occurrence and Meterological Data

The number of cold fronts passing over the Barataria Basin between September 1995 and April 1996 was counted by identifying the distinctive signature of cold fronts in the water level record obtained at Ugly Shack Bayou. Thus, only cold fronts that produced an identifiable response in water levels at Ugly Shack Bayou were counted. Although cold fronts can be identified by changes in barometric pressure, air temperature, or wind direction (Roberts et al. 1987), for this study changes in water level were used to identify cold front passages to ensure that all fronts that were counted produced a significant response in bay water levels, and thus had the potential to result in sediment transport. This method of counting frontal passages may have resulting in some weak fronts which did not produce identifiable responses in the bay water level not being counted.

Necessary features of a frontal passage signature include: prefrontal period of rising water levels lasting one or more days; frontal passage stage including a large drop in water level in excess of the tidal water level drops that occurred during the prefrontal stage and lasting less than one day; post-frontal stage characterized by damped tidal water level fluctuations typically lasting about one day. Wind speed and barometric pressure data were collected by the National Oceanic and Atmospheric Administration at Grand Isle, Louisiana, at the southern end of the Barataria Basin approximately 20 km SSE of the study site. Rainfall data were measured at various locations in southeastern Louisiana and reported by the Louisiana Office of State Climatology at Louisiana State University in Baton Rouge, LA.

Seasonal Variations in Water Level

Seasonal and annual variations in water levels in Barataria Bay were examined using water level records from Grand Isle, Louisiana, at the southern boundary of the Barataria Estuary. Records collected by the National Oceanic and Atmospheric Administration during 1995 and 1996 were compared with N.O.A.A. long term records collected from 1981 to 1994 to determine how seasonal water level fluctuations during the study period compare to typical conditions represented by the long term data.

RESULTS

Total suspended solids (TSS) concentrations in Live Oak Bay are quite variable, ranging from 15.1 to 265 mg l^{-1} during this study. TSS in the bay was measured 37 times spread throughout the year; average TSS for the entire study was

59.2 mg l^{-1} in the bay. Summer (April through September) TSS averaged 45.9 mg l^{-1} for 16 samples, with variance $s^2 = 42.8$; winter TSS (October through March) averaged 69.4 mg l^{-1} for 21 samples, with variance s= 59.3. Measured TSS concentrations in Live Oak Bay are shown in Fig. 4. Also shown in Fig. 4 are seasonal average TSS concentrations reported by Garrepally (1996). These measurements were made throughout the Barataria Basin in conjunction with the project reported here.

Sediment Deposition and Burial

New ^{7}Be inventory and atmospheric ^{7}Be deposition are shown in Fig. 5, and short-term mass sediment deposition data are shown in Fig. 6. These data are from cores collected at a site near the mouth of Ugly Shack Bayou and were presented by Rovansek et al (1997). The ^{7}Be technique employed by these collaborating researchers (Dr. Brent McKee and Greg Booth of the Louisiana Universities Marine Consortium, Chauvin, LA) employs a naturally occurring radionuclide of atmospheric origin as a tracer of suspended sediments in the estuary. Important aspects of their techniques are described below.

Sediment deposition and burial rates were quantified by measuring the naturally occurring radioisotopes ^{7}Be ($t^{1/2}$ = 53.3 days). ^{7}Be is produced by cosmic ray spallation reactions with nitrogen and oxygen in the atmosphere. ^{7}Be is delivered to the surface of the earth through precipitation (wet and dry) where it quickly adsorbs to particle surfaces and is subsequently deposited to bottom sediments in coastal margin environments. The half-life of ^{7}Be (53.3 days) enables it to be useful

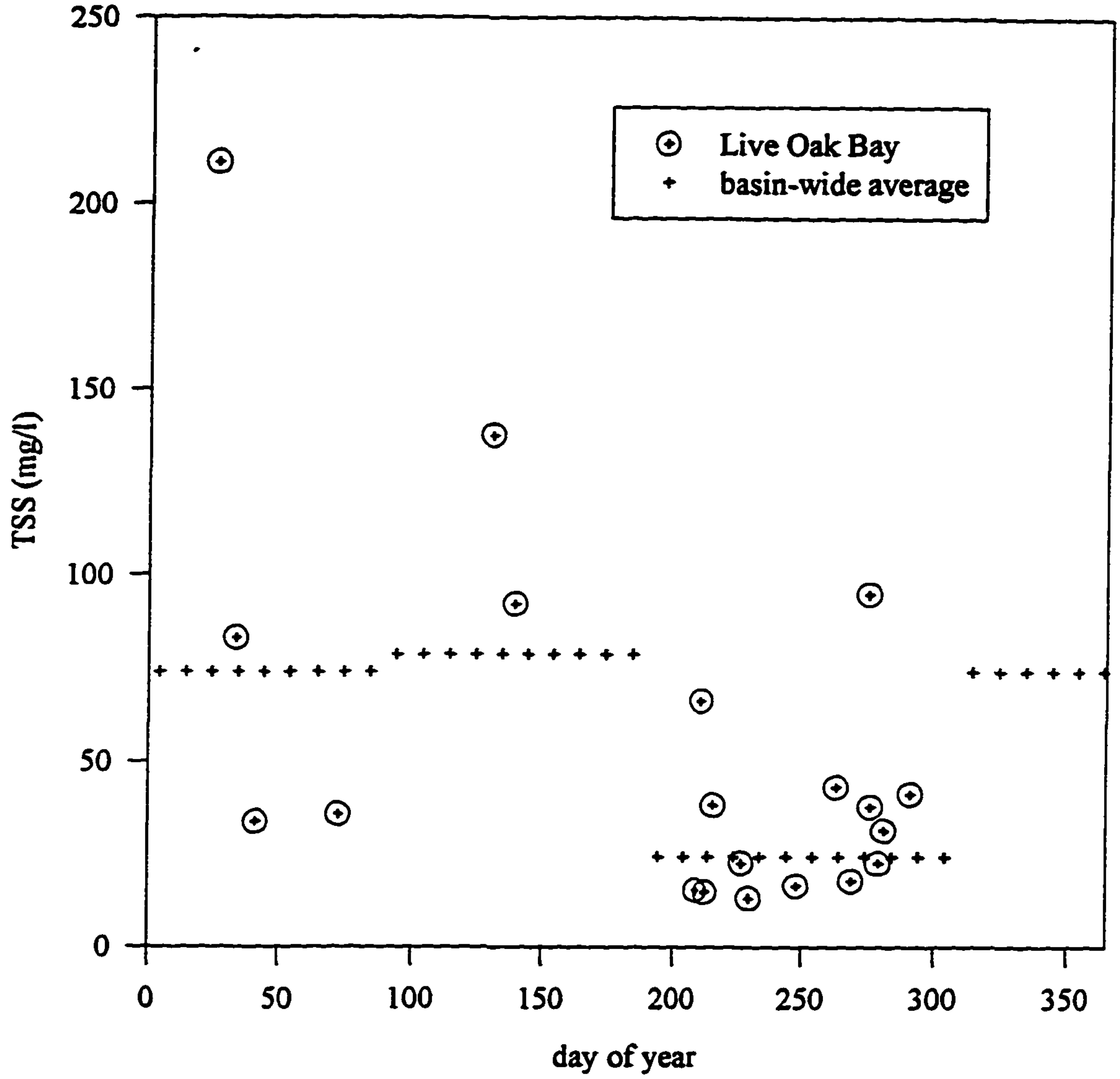


Figure 4. TSS in Live Oak Bay and basin-wide seasonal average values. Seasonal averages values from Garrepally (1996).

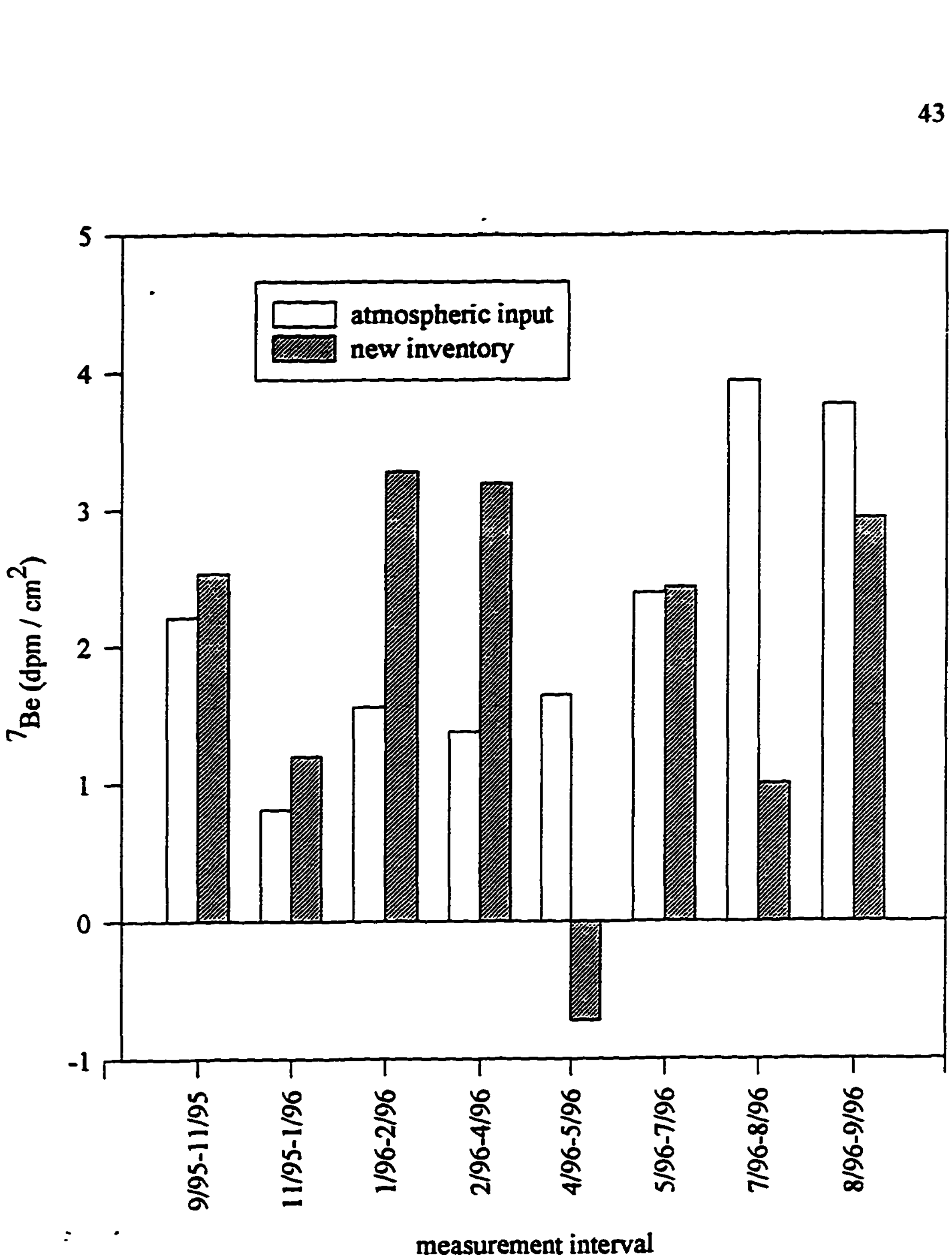


Figure 5. New ^{7}Be inventory and atmospheric ^{7}Be input at the Live Oak Bay bottom sediment sampling site. Adapted from Rovansek et al. (1997)

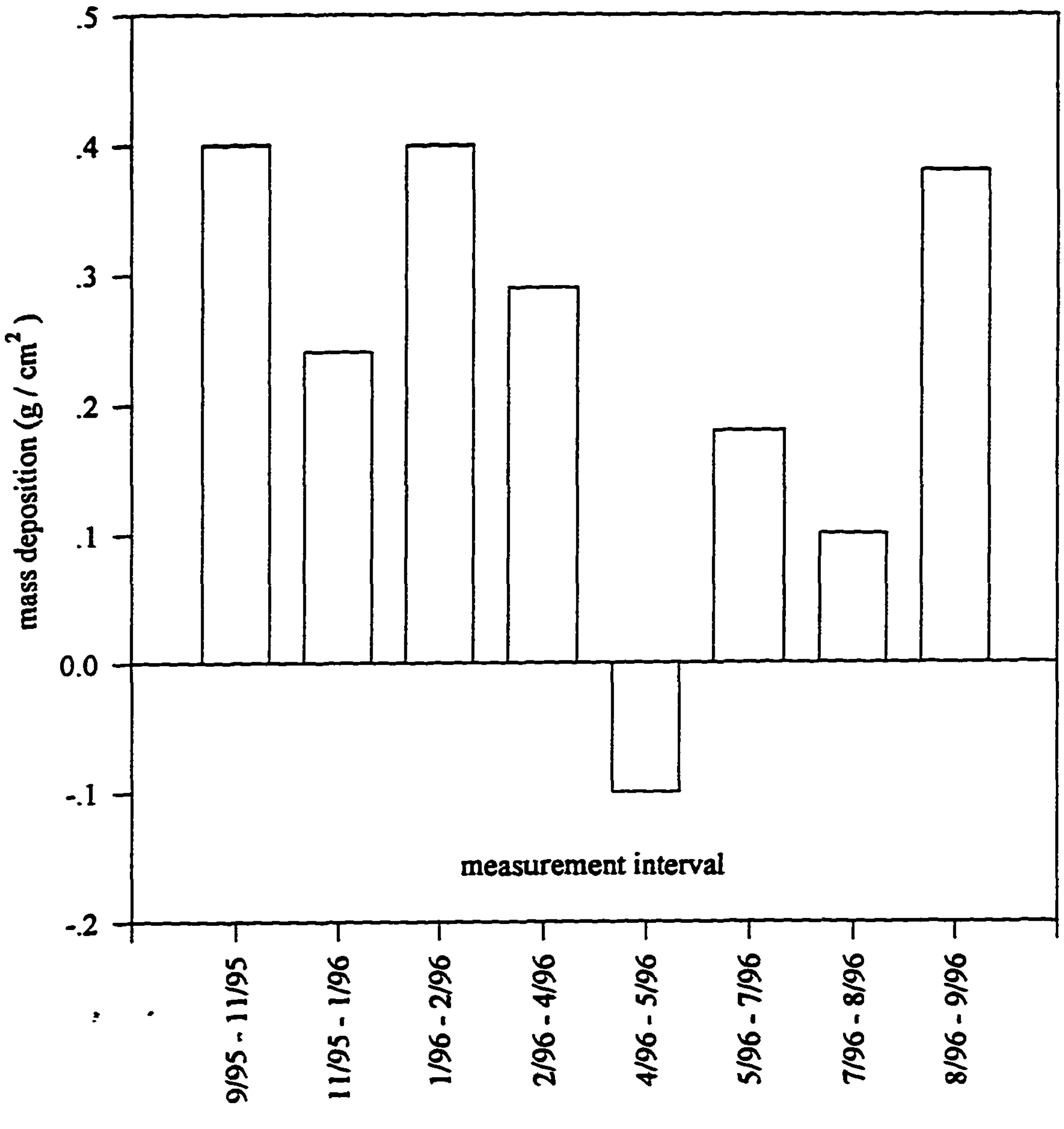


Figure 6. Mass deposition of sediment on the bottom of Live Oak Bay (Rovansek et al. 1997)

as a particle tracer on time scales of days to months. Sediment cores and rainwater were collected for radiochemical analyses at 4 to 6 week intervals in Live Oak Bay at a station near the mouth of Ugly Shack Bayou.

Monitoring the atmospheric input of ^{7}Be in conjunction with bottom sediment ^{7}Be inventories (0-3 cm depth) yields insight into short-term particle transport. By summing the inventory of ^{7}Be in each subsection of a core a total inventory is obtained which integrates over the depth scale of interest. Total inventories are made up of two components: residual inventory and new inventory. The residual inventory is the ^{7}Be inventory of the previous sampling period decay corrected to the present sampling period. The new inventory is the difference between the total inventory minus the residual inventory. Therefore, if the total inventory is equal to the residual inventory (i.e. the total inventory was entirely residual) then this would indicate no net sediment delivery or loss during the sampling period. If the residual inventory is greater than the total inventory this would indicate net sediment removal during the sampling period, and if the residual inventory were less than the total inventory this would indicate net sediment deposition during the sampling period. Short-term sediment deposition rates are calculated based on the following formula: Mass Deposition (g cm^{-2}) = New Inventory (dpm cm^{-2}) / *Mean New Activity (dpm g^{-1}) *(The mean new activity is the average activity of the newly deposited inventory).

<u>Seasonal Water Level Variations and Marsh Surface Inundation</u>

Water levels in the Barataria Basin fluctuate in a consistent pattern over the year (Baumann 1987). Figure 2 demonstrates the annual pattern of water fluctuations at Ugly Shack Bayou relative to the average water level measured between May 1995 and May 1996. Also shown in Fig. 2 is the percent of time that the marsh at the study site was inundated, on a monthly basis, during this study. Similar data presented by Baumann (1987) are included for comparison (Fig. 2).

Suspended Sediment Flux

Calm weather TSS fluxes resulting from tidal currents are reported in Table 2. Storm driven TSS fluxes are reported in Table 3. Data related to calm weather TSS fluxes during June, 1995 are shown in Fig. 7. Data relating to TSS flux during two winter cold fronts are shown in Fig. 8 and Fig. 9. Data relating to TSS flux during the passage of a topical depression, which late became T.S. Dean, are shown in Fig. 10.

VSS was found to consistently comprise approximately 25% of TSS both in Live Oak Bay and in Ugly Shack Bayou regardless of the season, weather pattern or tidal stage. Occasional aberrant VSS/TSS ratios were probably the result of the presence of a few large volatile particles in the sample. In addition to the generally high loading of small particulates in the bayou, large organic particles, including pieces of marsh vegetation and algae, are generally present and have the potential to greatly bias an individual sample toward a high VSS/TSS ratio. The generally constant VSS/TSS ratio means that VSS flux is a constant fraction of TSS flux. An additional concern with measured VSS values is that VSS results are less consistently available here than TSS, meaning that for several of the tidal fluxes for which net TSS flux is reported VSS flux could not be estimated. Therefore, discussion below

Table 2. Calm weather TSS fluxes at Ugly Shack Bayou.

Date	8 Jun 95	28 Jul 95	8 Oct 95	17 Oct 95	1 Feb 96
Elapsed Time (hh:mm)	20:00	24:00	26:20	26:20	24:20
Season[a]	Summer	Summer	Fall	Fall	Winter
Net TSS flux (kg)[b]	-1900	-1900	+190	+1200	+1100
Net TSS as %[c]	-83	-45	+4	+34	+17
Minimum water level (cm)[d]	-38.8	-45.5	-21.0	-26.3	-40.1
Maximum water level (cm)[d]	-9.0	-10.5	+3.7	+1.0	-5.9
Net change in water level (cm)	-9.6	+4.2	+3.1	-0.2	-0.1
Net water flux as %[e]	-95	+4	+3	+15	+21
Avg. flood tide TSS (mg/l)	19.8	28.9	43.4	32.8	53.5
Avg. ebb tide TSS (mg/l)	27.5	43.4	39.3	27.6	56.6
TSS difference (flood-ebb) (mg/l)	-7.7	-14.5	+4.1	+5.2	-3.1
TSS difference as %[f]	-33	-40	+10	+17	-6
Estimated TSS flux (kg)[b]	-600[g]	-1900	n/s[h]	+60[g]	n/s[i]

[a] seasons are defined based on sediment dynamics. see text

[b]positive values indicate net sediment import into bayou, negative indicate net export. figures reported are rounded off based on the estimated 15% error of measurement

[c]net TSS expressed as a percent of the average gross flood and ebb TSS fluxes. In order to exceed estimated measurement error net TSS (%) must be greater than 15%.

[d] minimum and maximum water levels measured relative to marsh surface

[e] net water flux expressed as a percent of the average flood and ebb tidal prism volumes.

[f] TSS concentration difference (flood TSS-ebb TSS) expressed as percent of the overall average TSS concentration. In order to exceed estimated measurement error TSS difference (%) must exceed 9%.

[g]due to large net water flux, the TSS flux that would be expected for a tidal cycle with no net water flux is estimated by multiplying the difference between ebb and flood TSS concentrations by the average of the flood and ebb tidal prism volumes.

[h]net TSS flux and TSS difference as % are both at or below estimated measurement error, therefore no significant net TSS flux could be identified from data.

[i]net TSS import (%) is less than net water import (%), and TSS difference (%) is less than estimated error of measurement, therefore no significant TSS flux could be identified from the data.

Table 3. Storm-driven TSS fluxes at Ugly Shack Bayou.

Event	Tropical depression passage	Cold front passage	Cold front passage
Date	4 Aug 95	15 Oct 95	28 Jan 96
Elapsed Time (hrs)	169	124	71
Season	Fall	Winter	Winter
Net TSS flux (kg)[b]	+56,000	+1,900	+18,000
Net TSS as %[c]	+77	+6	+77
Minimum water level (cm)[d]	-41.2	-42.0	-46.7
Maximum water level (cm)[d]	+33.0	+8.8	+2.3
Net change in water level (cm)	+45.5	-15.3	-0.7
Net water flux as %[e]	+18	0	+20
Avg. flood tide TSS (mg/l)	66.9	41.0	153.9
Avg. ebb tide TSS (mg/l)	52.5	38.7	65.9
TSS difference (flood-ebb) (mg/l)	+14.5	+2.3	+88.0
TSS difference as %[f]	+24	+6	+80
Estimated TSS flux (kg)	+56,000	n/s[g]	+18,000

[a] seasons are defined by sediment dynamics. see text
[b]positive values indicate net sediment import into bayou, negative indicate net export. reported figures are rounded off based on estimated error of 15%
[c]net TSS expressed as a percent of the average gross flood and ebb TSS fluxes. In order to exceed estimated measurement error net TSS (%) must be greater than 15%.
[d]minimum and maximum water levels measured relative to marsh surface
[e]net water flux expressed as a percent of the average flood and ebb tidal prism volumes.
[f]TSS concentration difference (flood TSS-ebb TSS) expressed as percent of the overall average TSS concentration. In order to exceed estimated measurement error TSS difference (%) must exceed 9%.
[g]net TSS flux and TSS difference as % are both at or below estimated measurement error, therefore no significant net TSS flux could be identified from data.

will mention only TSS fluxes; VSS fluxes are assumed to follow the same trends described for TSS. In studies of suspended sediment flux such as this one, the

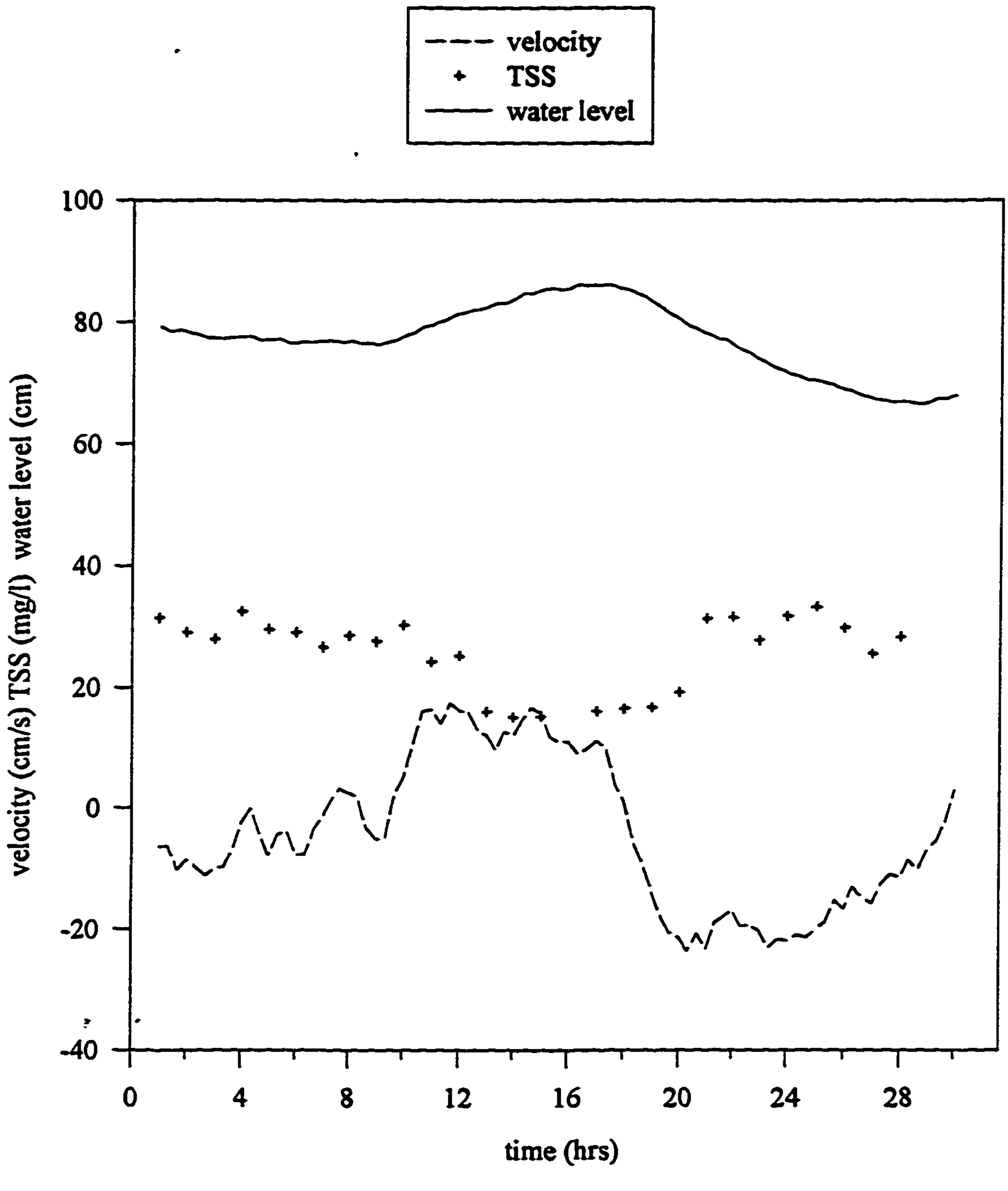


Figure 7. Sediment flux data for June 7-8, 1995 at Ugly Shack Bayou. Positive velocities represent flow into the bayou.

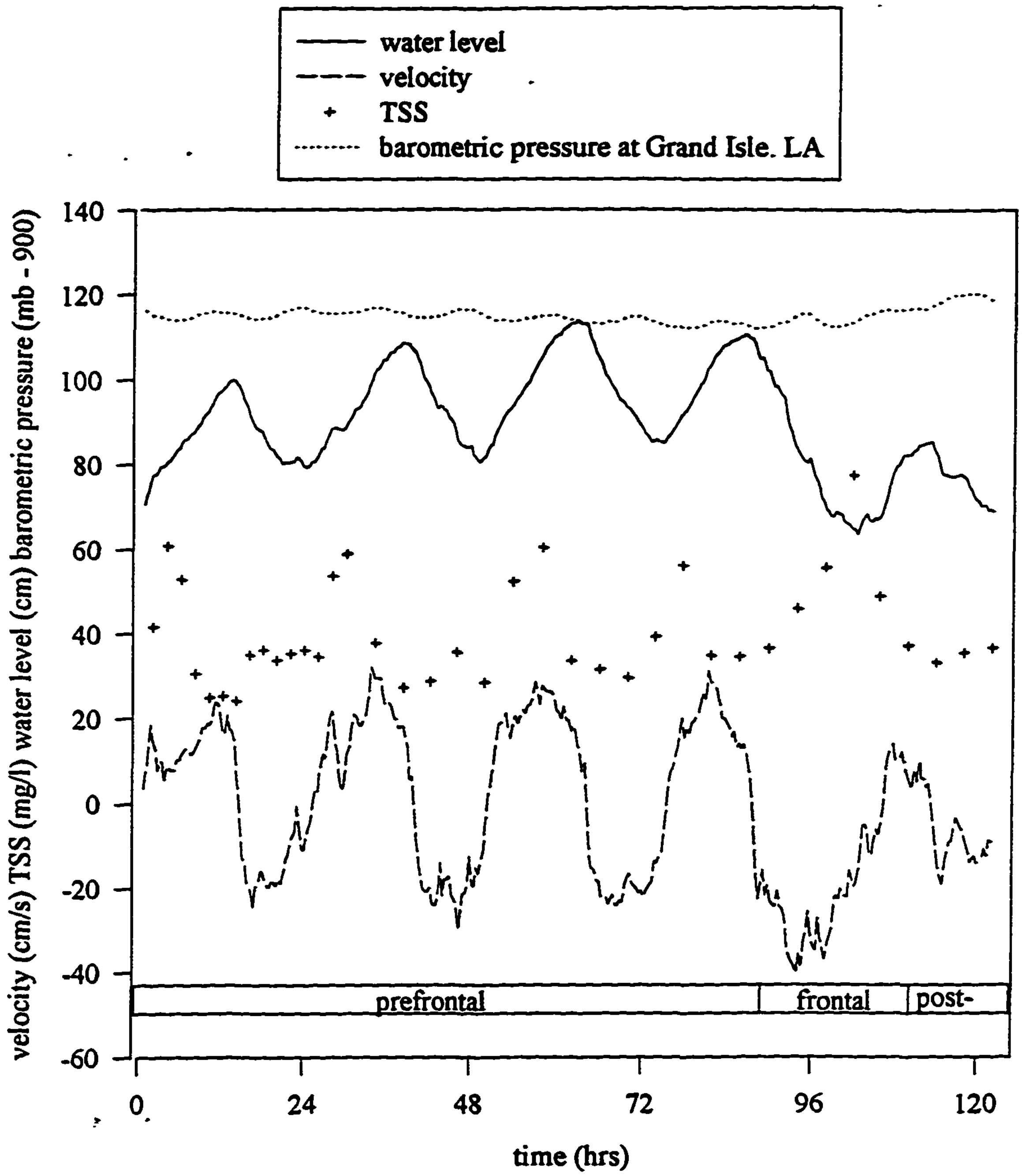


Figure 8. Sediment flux data for cold front passage Oct. 10-15, 1995.
Positive velocities indicate flow into the bayou.

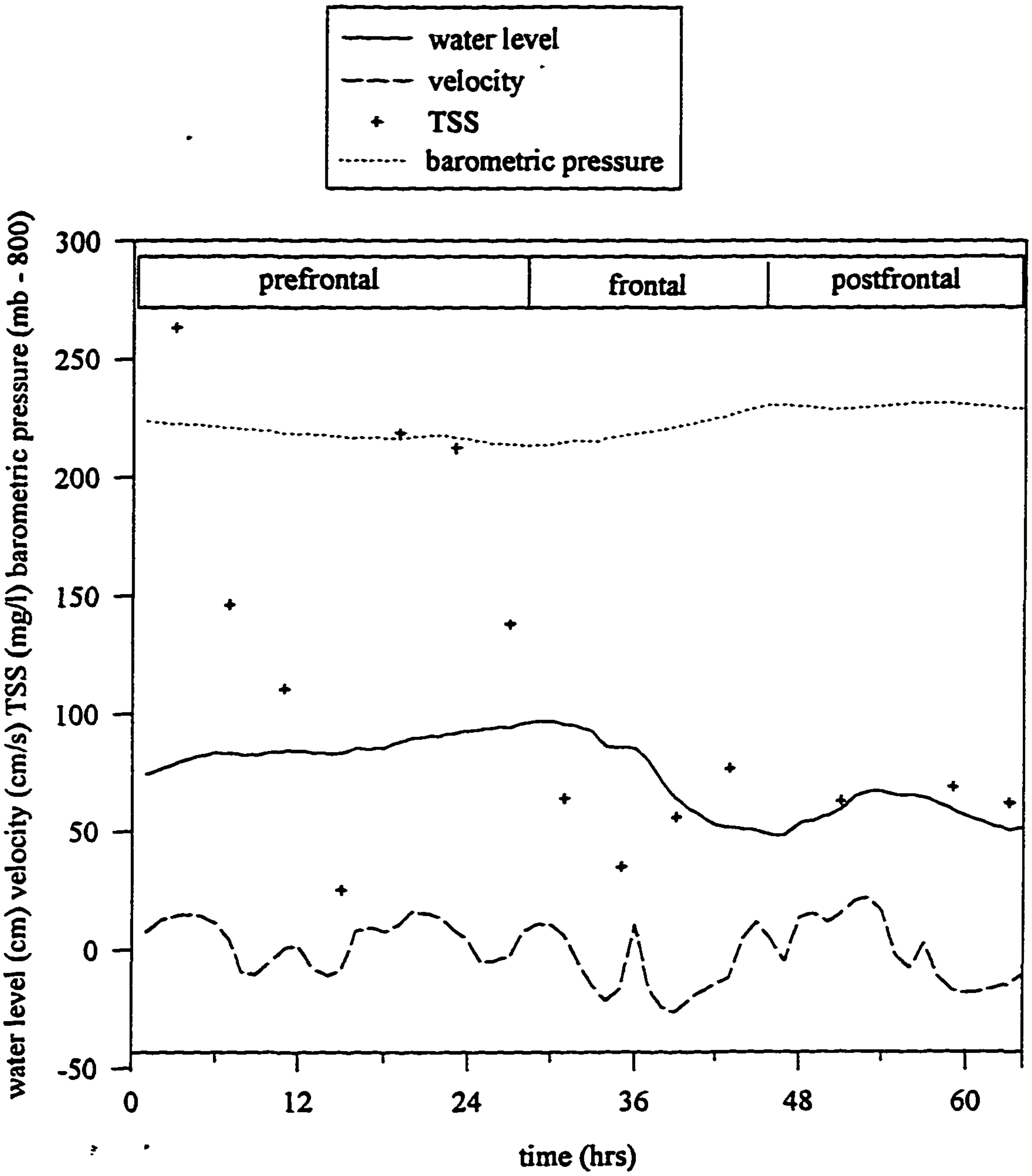


Figure 9. Sediment flux data for cold front passage, January 25 through 28, 1996. Positive velocities indicate flow into the bayou.

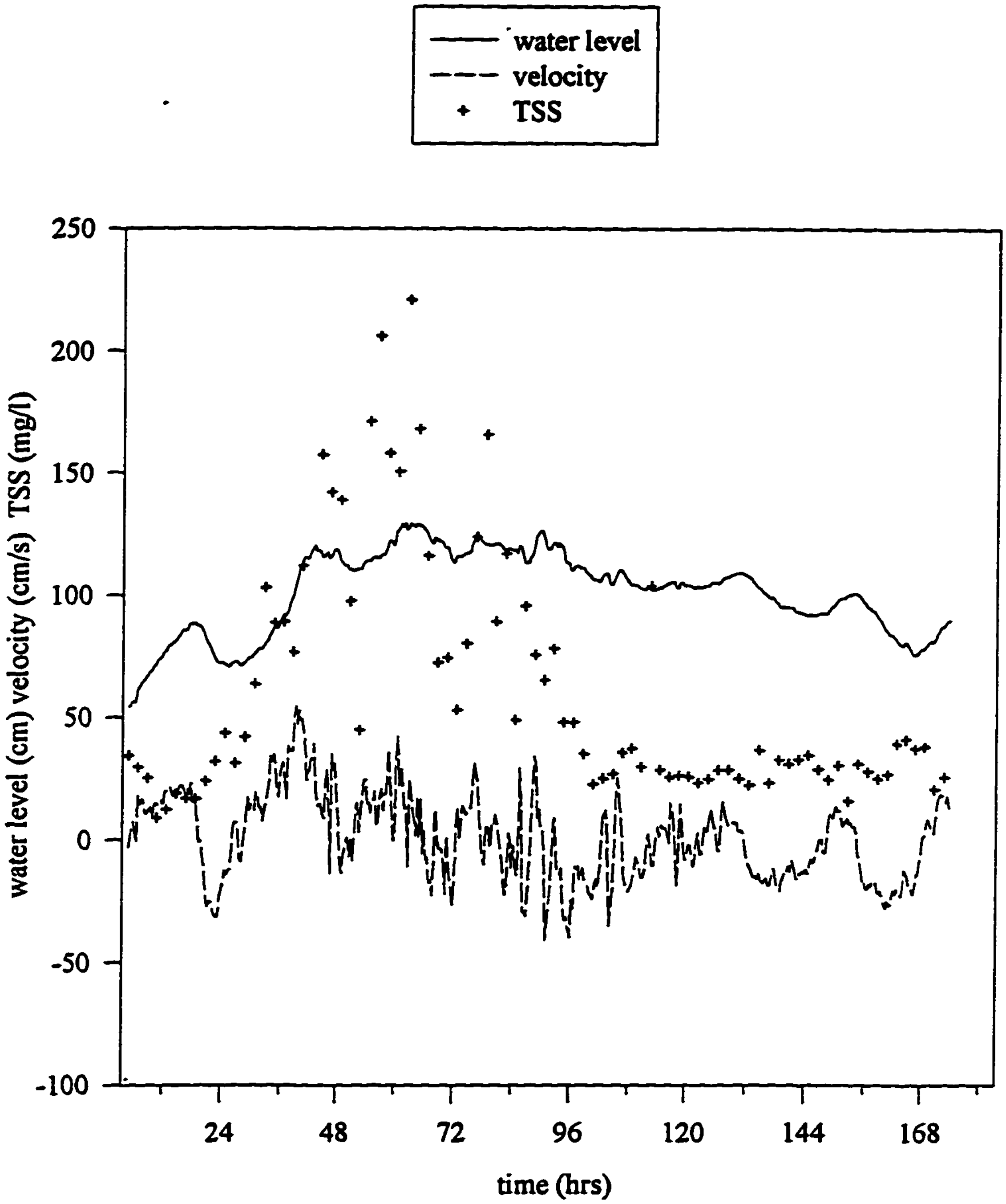


Figure 10. Sediment flux data during passage of tropical depression, July 28 through August 4, 1995. Positive velocities represent flow into the bayou.

reliability of measured fluxes must be considered. Various researchers have investigated the accuracy of flux measurements in tidal channels and have suggested several different approaches to insuring estimate reliability.

Ward (1981) suggested that ebb or flood bias in water flux estimates be detected by examining net water inflow and outflow over a tidal cycle. Net discharge should be zero between occurrences of a given tidal stage. Spot-checks of net water flux throughout the study period demonstrate that net water fluxes are usually small between occurrences of a given tidal stage, indicating that measurements are neither consistently flood nor ebb biased.

Measuring water velocity and suspended sediment concentration at one or a few points in the bayou cross-section rather than using a larger number of velocity measurements spaced throughout the bayou cross-section introduces error into the estimation of net TSS flux. Roman (1984) measured velocity in a tidal channel using a dense array of 18 current meters. He found that calculations using the most optimal of the 18 points resulted in estimates of instantaneous water discharge within 11% and net tidal cycle flux within 7% of estimates produced using the dense sampling array. Leonard et al. (1995) studied a micro-tidal marsh creek with a cross-section similar to the bayou studied here and found that a single point velocity measurement within the tidal creek approximated average velocity in the creek within 13% error of the estimate made using 7 velocity measurements along a vertical section of the creek. Including the error associated with measurement of suspended sediments at a single point and the error associated with measuring TSS only once (no replicates), Leonard et al. (1995) determined that an error of 16% was associated with their estimates of suspended sediment flux. Ward (1981) measured suspended sediment flux in a tidal creek using an array of 6 velocity sensors arranged in three pairs. Each of three transverse channels sections had a pair of velocity sensors at approximately 20 and 80 percent of the total depth at the section, similar to the arrangement of our single pair of sensors. The author determined that spatial and temporal errors on the order of 10 to 15% are associated with his estimates of suspended sediment flux, and argued that measured net flux over the course of a tidal cycle must therefore exceed 15% of the average of the flood and ebb fluxes in order to be considered significant.

Based on the results of Ward (1981) and Leonard et al. (1995), error associated with our estimates of suspended sediment flux are assumed to be approximately 15%. Our net flux estimates are divided by the mean flood and ebb TSS transport to determine the percent of total transport represented by net flux. When the magnitude of the net flux is less than 15% of the average of the flood and ebb transports, our results are not considered significant.

Many of the tidal cycles reported show a non-zero net water balance. This may represent a real net change in water, as is evident in the data from the June 8, 1995 tidal cycle (Table 2). Other non-zero net water fluxes (February 1, 1996 and October 17, 1995) are not apparently the result of changes in water level (Table 2). These net changes (15 and 21%) are of the same magnitude as estimated errors (15%), and thus may represent measurement error.

TSS concentrations during flood and ebb tides are an important component of TSS flux (Table 2). Leonard et al. (1995) found that an error of approximately 9% is associated with use of TSS measurement at a single point to characterize the average concentration in a tidal creek as was done here. Thus, where flood and ebb averages differ by more than 9%, a significant difference is considered to exist. Water flux is also an important component of TSS flux, therefore the net water flux measured over a tidal cycle must be considered in the determination of the significance of measured TSS flux. Where substantial differences exist between measured flood and ebb water fluxes (i.e. there is a substantial net water flux over the tidal cycle or storm event), estimates of the magnitude of actual TSS fluxes are based on flood and ebb TSS concentrations and average tidal prism volume.

Calm Weather TSS Flux

Calm weather TSS fluxes are often within the range of measurement error. Therefore, in order to determine which data sets indicate sediment flux in excess of estimated measurement error, each data set was examined carefully with respect to several criteria. The net water flux for each measurement period was considered as a component of net sediment flux. Although net water flux may result in a net TSS flux for a given measurement interval, net water flux for any long interval of time would be near zero, and so it is not desirable to include the effects of temporary net water flux in estimates of TSS flux. Where a large net water flux existed, the relative magnitudes of the net water and TSS fluxes, as well as other criteria, were considered before a measured TSS flux was considered a real flux in excess of estimated measurement error. Additional criteria that were examined include the average TSS concentrations measured in the bayou during the flood and ebb tides and the difference between the two average TSS concentrations. A TSS difference larger than the estimated measurement error of 9% was considered an indicator of net sediment flux. Data used to determine the significance of measured sediment fluxes are shown in Tables 2 and 3.

Net TSS flux for the tidal cycle of October 8, 1995 is 4% of the flood/ebb average TSS transport (Table 2), and thus cannot be considered significant. Similarly, flood/ebb TSS averages differ by only 10%, very near the magnitude of estimated error (9%) and therefore the difference is not considered significant. The TSS flux for October 17, 1995 is 34% of the flood/ebb average, while net water flux is 15% of flood/ebb average and is, like TSS flux, in an inland direction (Table 2). The net TSS flux is far greater than the net water flux indicating that the measured import is not solely due to the large net water flux. Flood TSS averages 17% larger than ebb; this substantial difference supports the measured flux. Thus, the October 8, 1995 tidal cycle is considered to have no significant flux, while the October 17, 1995 cycle has a significant net flood flux of TSS. Based on difference between ebb and flood TSS concentrations and the tidal prism volume, estimated net TSS flux which would be expected for a tidal cycle where no net water flux occurred for October 17, 1995 is 600 kg TSS.

The June 8, 1995 TSS flux is large and in the ebb direction (Table 2). This is partly the result of a large ebb balance of water flux that was the result of an almost

10 cm net lowering of water level over the course of the tidal cycle. Examination of the measured TSS concentrations during the flood and ebb portions of the tide shows that ebb TSS concentrations were significantly higher than flood concentrations indicating that a net ebb flux of TSS would be expected even given a zero net water balance. The July 28, 1995 flux data show a 45% net ebb TSS flux with a near zero net water flux (Table 2). This net flux is supported by TSS concentrations, which are 40% higher during ebb than during flood; this difference is also considered significant. Both the June and July tidal cycle data thus show a significant ebb-directed flux of TSS. Based on TSS concentrations and tidal prism volume the June tidal cycle flux is estimated to be 600 kg TSS. The July tidal cycle flux is 1900 kg TSS.

The February 1, 1996 flux measurements show that the 17% net flood TSS flux is less than the 21% net flood flux of water (Table 2). TSS concentrations are slightly lower during flood than during ebb. The small difference in flood and ebb TSS concentrations suggests that no significant net flux due to tidal exchange can be determined from the February data.

Storm-Driven TSS Fluxes

TSS flux measurements made from July 29, 1995 through August 4, 1995 document the effects of the passage of a tropical depression, which later became Tropical Storm Dean (T.S. Dean), through the central Gulf of Mexico south of the Barataria Basin (Table 3). The storm's passage resulted in a large rise in water level, a large flood-directed water flux, high suspended sediment concentrations, and a large inland flux of TSS at Ugly Shack Bayou (Fig. 10). The inland flux of 56,000 kg of TSS makes T.S. Dean the largest sedimentation event recorded during this study. Net TSS flux is 77% of the average of gross flood and ebb TSS fluxes, and flood TSS concentrations are significantly higher than ebb concentrations (24% larger). Measurement of TSS at the station ended before water level returned to pre-storm level at the bayou resulting in a large net movement of water. This probably contributed somewhat to the net TSS flux recorded at the station because the excess water would be expected to carry some TSS with it when it finally drained from the marsh. Assuming that the excess water exits the marsh carrying typical pre-storm ebb concentrations of TSS would account for only 8200 kg TSS, leaving a net inland flux of almost 48,000 kg TSS. This would still make T.S. Dean's passage the largest sediment flux event recorded.

The passage of a cold front was recorded between October 10 and October 15, 1995 (Table 3). This storm resulted in a rise in water level relative to pre-storm levels, and a large movement of TSS. Net TSS movement was inland and was 6% of the average of gross flood and ebb TSS fluxes. This is less than the estimated error of 15%. The difference between flood and ebb TSS concentrations is also less than estimated error, and thus no significant movement of sediment can be identified. A cold front passage during January 25 through January 28, 1996 resulted in a net inland flux of TSS that was 77% of the flood/ebb average gross flux (Table 3). This inland flux is supported by average flood TSS that was 88 mg/l greater than the average ebb concentration. This represents an 80% difference that exceeds the estimated 9% error in measurement. Based on the difference between flood and ebb TSS concentrations and the average of inflow and outflow during the period, the net flux resulting from the January cold front is 21,000 kg TSS moving into the bayou and marsh. The reasons for the dissimilar sediment fluxes resulting from the two fronts will be discussed later in this chapter.

Annual Sediment Budget for Ugly Shack Bayou

Estimating a net sediment budget for Ugly Shack Bayou using a limited number of measurements of TSS flux requires that flux occurring during unmeasured intervals be estimated based on flux observed during measurement intervals. Therefore it is desirable to identify seasons when conditions that are expected to influence sediment flux remain relatively constant. Based on observed water levels, measured TSS flux, and dominant weather patterns, and considering the small number of flux measurement periods available, the year is divided into three seasons. It should be noted that the three seasons described below are distinguished by weather patterns and water levels, and thus their duration and timing will vary from year to year. Definitions of the seasons are followed by a description and estimation of the total sediment fluxes during the several seasons.

During May, June, and July 1995 water level remains below the surface of the marsh at Ugly Shack Bayou most of the time (Fig. 2). This period occurs after the passage of cold fronts, which are a typical feature of the weather in southeast Louisiana during the winter, has generally stopped and before tropical weather systems become frequent and water levels rise in the Gulf of Mexico (Fig. 2). The "summer" season usually consists of May, June, and July. Water level at Ugly Shack Bayou rises during late-summer, mirroring a trend that is typical for the northern Gulf of Mexico (Baumann 1987). The "fall" season includes the months of August, September, and October. The "winter" season begins with the initiation of cold frontal passage, usually in October, and is characterized by cold frontal passages and low water levels. Winter includes November, December, January, February, March, and April.

Calm weather TSS fluxes reported during summer are ebb-directed indicating that Ugly Shack Bayou exports TSS during the summer in the absence of storm activity. Averaging the July tidal cycle (1900 kg) and the estimated net flux expected if the June cycle had a net water balance (600 kg) yields an average tidal export of 1,250 kg TSS cycle^{-1}. The diurnal tides in Barataria Bay result in approximately 30 tides per month, and a net export of 37,500 kg TSS month^{-1} would be expected as a result of calm weather flux. This amounts to a discharge from the bayou/marsh of 112,500 kg TSS Summer^{-1}.

Calm weather flux measurements during Fall indicate flood-directed flux (October 15-17, 1995) or flux less than estimated error (October 7-8, 1995). Averaging the two flux estimates (600 and 0 kg (tidal cycle)$^{-1}$) yields an average import of 300 kg TSS (tidal cycle)$^{-1}$, 9,000 kg TSS month^{-1}, or 27,000 kg TSS Fall^{-1}. Storm driven flux measured during Fall was controlled by the passage of a tropical weather system. The occurrence of tropical weather is erratic, and therefore these events will be considered separately from other events in the calculation of annual net flux. The cold-front passage measured during October 1995 will be included with the winter season, because the initiation of cold front passages has been defined here as the beginning of the winter season.

Calm weather fluxes measured during the winter are less than the estimated error of measurement (Table 2). Thus it appears that tidal action has a negligible effect on net sediment movement during winter. Winter cold front passages include one event that resulted in negligible net sediment movement (October 15, 1995) and one that resulted in net sediment import into the bayou (January 28, 1996), with an average net sediment import of 10,500 kg TSS (cold front)$^{-1}$. According to water levels recorded at Ugly Shack Bayou, 25 fronts passed over Barataria Bay between September 1995 and April 1996. This is an average number of fronts for a winter based on the estimate of Roberts et al. (1993) that 20 to 30 cold fronts pass through coastal Louisiana each winter. Based on the above estimate of average TSS transport per front, the passage of 25 fronts would result in the import of 262,500 kg TSS Winter^{-1}. This is both an estimate of TSS transport during winter 1995-1995 and transport during an average winter because the 25 fronts that passed during the winter studied is an average number (Roberts et al. 1987).

The estimated net sediment flux in Ugly Shack Bayou during the first year of this study, May 1, 1995 through April 30, 1996 was an net import of 233,000 kg TSS. Based on seasonal estimates presented above, the average net annual TSS flux at Ugly Shack Bayou is a net import of approximately 177,000 kg TSS year^{-1}. This estimate neglects the effects of late-summer storm activity such as T.S. Dean, which are potentially great. It is difficult to assess the accuracy of the annual flux estimate. Errors associated with the estimate include measurement errors in the values of TSS and velocity, as well as error associated with variability between tidal cycles during a given season and errors in correctly assigning the length of the seasons. The latter two sources of error are probably much larger than the former, which has been estimated to be approximately 15%. Interannual variability in average tidal flux and in duration of the several seasons provides another source of uncertainty in the estimate. While the magnitude of the estimate is subject to large uncertainty, the large net inland flux estimated above, combined with the exclusion of storms that result in potentially large inland sediment fluxes, suggests that the direction of the flux estimate is reliable, and that net sediment movement is inland on an annual basis.

The four late summer storm events (Table 4) recorded during 1996 included one with stronger winds, longer duration of marsh inundation, and higher water levels than T.S. Dean (October 1, 1996), another with a longer duration of inundation and higher water levels but slightly lower wind speeds (August 20, 1996), and two with lower wind speeds, lesser duration of marsh inundation, and lower water levels than T.S. Dean. Thus, T.S. Dean falls approximately in the middle of the range of intensities of storms of this type that occurred during this study, and will be considered an approximately average storm of this type. T.S. Dean resulted in an import of about 56,000 kg TSS into Ugly Shack Bayou. The total of five similar events would result in the import of 280,000 kg TSS in two years, or an average of

140,000 kg TSS per season. Including late summer storms in the calculation of average annual sediment budget raises the net sediment import into Ugly Shack Bayou to 317,000 kg TSS $year^{-1}$. VSS makes up approximately 25 percent of the TSS passing our gaging station throughout the year. This is similar to the proportion of organic matter,

Table 4. Fall Season Storm Statistics during Sampling Periods

	Date	Time	dur. of inund (hrs)	max depth above marsh surf (cm)	wind dir[a] (deg)	average previous 48 hr wind speed[a] (m/s)	wind dir[a] (deg)	average previous 24 hr wind speed[a] (m/s)
T.S. Dean								
start	7-29-95	15:00	100	33	145	5.3	76	7.2
peak	7-30-95	17:00			79	9.4	92	11.2
end	8-2-95	19:00						
start	8-20-96	0:00	119	43	120	3.0	100	3.3
peak	8-22-96	12:00			87	7.5	85	8.4
end	8-24-96	23:00						
start	9-13-96	15:00	95	27	185	2.7	195	2.6
peak	9-16-96	9:00			174	5.0	177	6.2
end	9-17-96	14:00						
start	9-25-96	6:00	80	21	92	3.0	105	2.5
peak	9-27-96	22:00			150	5.1	168	6.0
end	8-24-96	23:00						
start	10-1-96	23:00	216	70	44	6.1	62	4.8
peak	10-5-96	12:00			49	10.6	59	11.9
end	10-10-96	23:00						

[a]meteorological data measured at Grand Isle, Louisiana (N.O.A.A.)

based also on loss by ignition, found by DeLaune et al. (1989) in marsh sediments at two sites in the southwestern Barataria Basin (28.1 and 32.0%). Thus, our suspended sediments are similar in makeup to marsh sediments in the area. DeLaune et al. (1989) found an average bulk density of approximately 0.18 g cm^{-3} in the upper 42 cm of salt marshes. Based on this, and the Ugly Shack Bayou drainage area of 710,000 m^2, our estimated sediment flux of 317,000 kg TSS $year^{-1}$ amounts to 0.24 cm of accreted sediments per year. Neglecting the effects of late-summer storms, the estimated annual flux of 177,000 kg amounts to 0.13 cm of accretion. It should be noted that the estimated accretion depths above are presented for the purpose of comparison with previously published measurements of marsh accretion, and are not meant to suggest that the sediment which was observed passing the Ugly Shack Bayou gaging station was deposited evenly on the marsh surface. Net sediment import estimated by this study will be compared with published measurements of sediment deposition below.

Sediment Erosion from the Marsh Surface during Rainfall

A 40 minute thunderstorm at the site on September 20, 1996 caused substantial erosion of sediment from the marsh surface, which was exposed by low water level during the storm. The storm resulted in the erosion and transport off the marsh surface of approximately 228 kg of TSS. The discharge of 228 kg from the 10,000 m^2 rivulet drainage basin is equivalent to a discharge of 16,200 kg TSS from the entire Ugly Shack Bayou drainage area. This sediment is transported from the marsh surface into the water and bottom sediments of the bayou, where it may be subject to eventual transport out of the bayou into the bay. Thus, rainfall has the potential to result in net removal of sediment from the bayou/marsh. More detailed results of the rivulet discharge study are presented in Chapter Four.

Seasonal Fluctuations on Water Level

Water levels recorded at Grand Isle, LA during 1995 and 1996 are shown in Fig. 11. The data shown in Fig. 11 were compared to long term data collected from 1981 to 1994 at Grand Isle by the National Oceanic and Atmospheric Administration. Although long-term data are not relative to the same datum as 1995/1996 data, several conclusions can be reached regarding the years during which this study took place. Figure 11 shows that seasonal water level fluctuations during both 1995 and 1996 followed a pattern similar to that described by Baumann (1987); water level are relatively low during the winter, rise during spring, and reach their highest levels during late summer and fall. This general pattern is evident in the long term record. Water levels, averaged over twenty day intervals, fluctuate over a range of approximately 0.58 m during 1995 and 0.76 m during 1996. The annual fluctuation during the thirteen years of the long-term record averaged 0.43 m; annual fluctuations in the long term record ranged from 0.67 m during 1985 to 0.25 m during 1983. The 1996 and 1995 fluctuations are the largest and third largest of the total of fifteen years' data available; this study took place during two years of higher than average seasonal water level fluctuations, although water level fluctuations follow the usual pattern of highest water levels during the late summer and fall. The higher than normal water level fluctuations during 1996 are largely due to a period

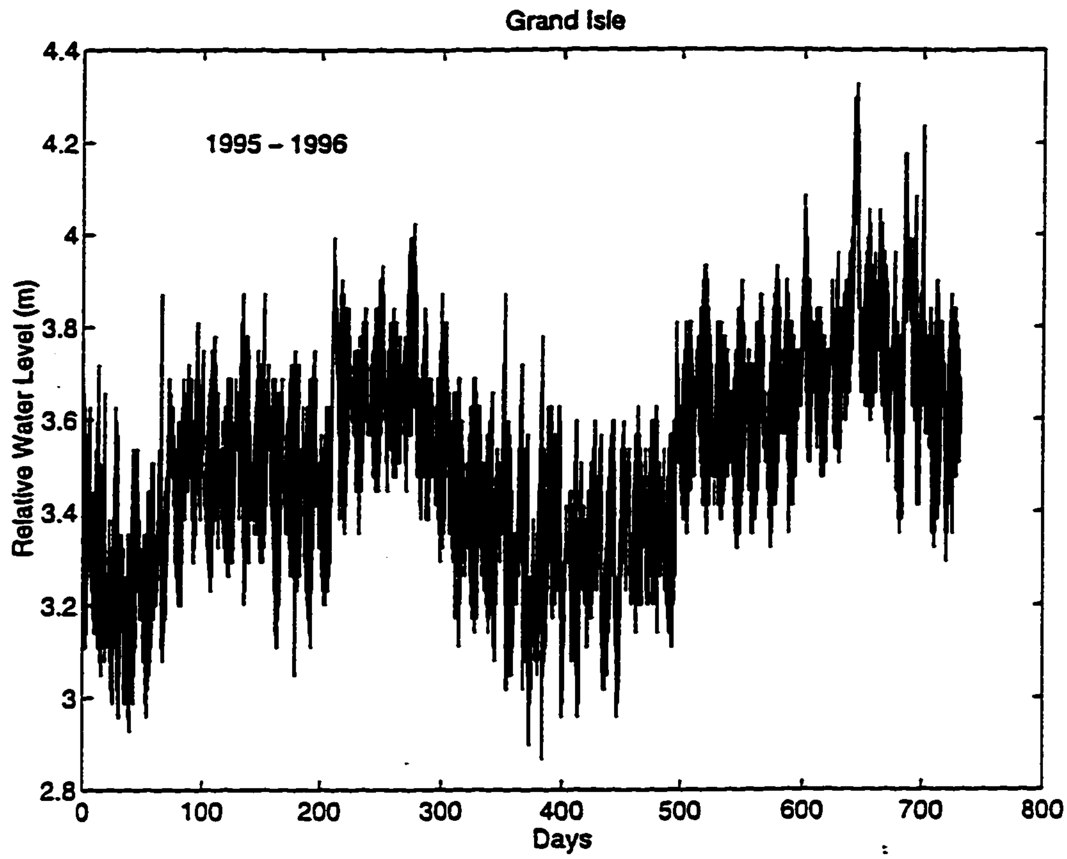


Figure 11. Relative water levels at Grand Isle, LA during 1995 and 1996. Days are elapsed days since Jan 1, 1995; hourly water levels recorded by N.O.A.A.

of very high water levels during October. Fluctuations during the rest of 1996 are of similar magnitude to that observed during 1995 and are within the range of fluctuations recorded during the long-term record, albeit somewhat higher than average. The implications of the unusually large water level fluctuations during this study will be discussed below.

DISCUSSION

The first part of this discussion will examine measured sediment fluxes in Ugly Shack Bayou and their relationships with physical variables including water level fluctuations, water currents in the bayou, and weather. The second section of the discussion will focus on the interactions between sediment flux in the bayou and sediment dynamics in adjacent Live Oak Bay.

Sediment Flux in Ugly Shack Bayou

Sediment flux measurements were made between June 1995 and February 1996. During this period water level followed a pattern of fluctuation similar to that reported by Baumann (1987); fluctuations at Ugly Shack Bayou relative to the annual mean water level were of similar magnitude to fluctuations reported based on long term average data (Fig. 2) with larger than normal fluctuations during 1996 due to exceptionally high water during the late summer and fall of 1996. This pattern is similar to that recorded at Grand Isle (Fig. 11). Marsh surface inundation at Ugly Shack Bayou followed the same pattern as reported by Baumann (1987), although percent inundation was less frequent at Ugly Shack Bayou throughout the year than reported by Baumann (1987) (Fig. 2). This indicates that the marsh surface at Ugly

Shack Bayou is elevated farther above mean water level than marshes at Baumann's (1987) site. Cumulative net sediment flux measured during the first year of this study (May 1, 1995 through April 30, 1996) is shown in Fig. 12. The negative net sediment flux during summer results from the net export of TSS during typical summer tidal fluctuations and a lack of storms, which are important agents of sediment import to the bayou. Net sediment export ceased with the passage of Tropical Storm Dean through the central Gulf of Mexico in early August (Fig. 12). This event resulted in a large net import of TSS, and coincided with the beginning of the fall season (as defined above based on sediment dynamics). Sediment import through fall resulted from net import of sediments during typical fall tidal fluctuations; fall is the only season during which sediment import was observed as a result of normal tidal currents in the bayou. The large import of sediments during the winter season is due to the occurrence of numerous cold front passages, whose occurrence is indicated in Fig. 12. Cold front passage does not occur uniformly throughout the winter, and as a result sediment import does not occur uniformly throughout the winter (Fig. 12).

Storm-Driven TSS Fluxes

Our measurements of TSS flux in Ugly Shack Bayou include five periods of tidally-controlled flux during relatively calm weather, and three storm events. Net inland flux of TSS was found during only one of the calm weather periods, while two of the three storm events resulted in net inland movement of sediments. Net bayward flux occurred during two calm weather periods, and no bayward flux was

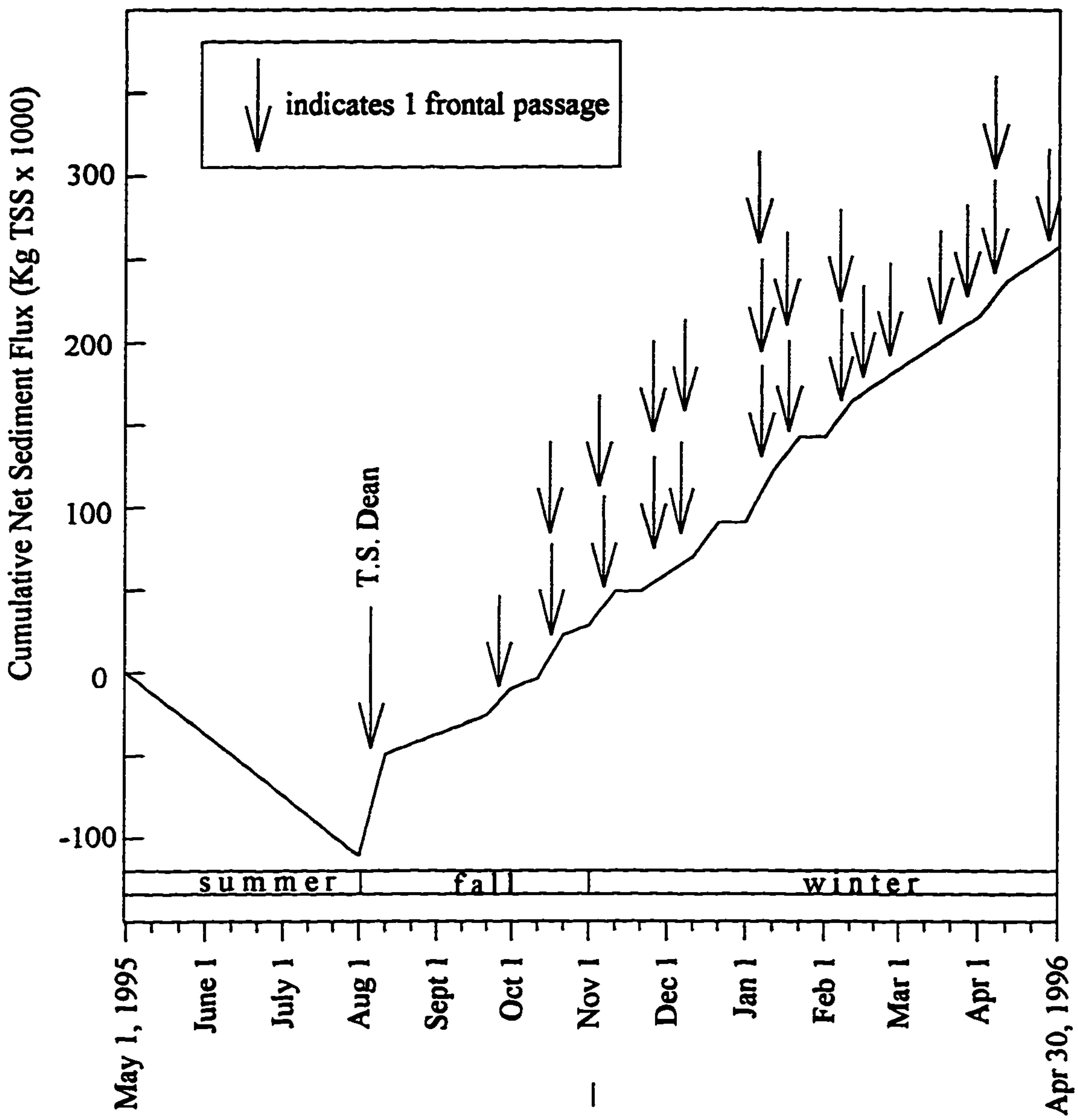


Figure 12. Cumulative net TSS flux in Ugly Shack Bayou May 1, 1995 to April 30,1996. TSS flux and storms shown for 10 day intervals.

found to result from storm events. Thus it is clear that net sediment movement into the bayou and marsh is mainly the result of storm events. The estimated annual sediment budget indicates that a large net inflow of sediments occurs annually. Again, this is clearly dominated by storm events.

The domination of the estimated annual sediment budget by storm-driven fluxes is largely the result of the large number of cold front passages that occur each winter on the Louisiana coast. Estimates of the annual number of cold front passages range from 20 to 30 (Roberts et al. 1989) to 30 to 40 (Moeller et al. 1993), with passages occurring between October and April. During our study winter of 1995/1996, 25 cold fronts of sufficient intensity to produce an identifiable response in recorded water levels passed over Barataria Basin. The variable intensity of cold front passages results in varying strength of winds, rains, and resulting waves and storm surges and is reflected in our results; one cold front resulted in a large net inflow of TSS in the bayou while the other did not produce significant flux. The reason for the dissimilar results obtained during our two cold front passages will be discussed below. Despite a range of intensities, cold front passages are known to have significant sedimentological and geomorphic impacts on Louisiana coastal environments as a result of the consistent succession of winds and water levels that they create (Roberts et al. 1987).

The passage of cold fronts through coastal Louisiana can be divided into three stages: prefrontal; frontal passage; and postfrontal. The prefrontal stage brings steady winds from a southerly direction which produce rising water levels at our site of as much as 0.6 m, and which resuspend sediment in shallow nearshore waters. This is reflected in the higher average TSS during flood tides than during ebb tides (Table 3), and can be seen in Fig. 8 and 9. The frontal stage is characterized by strong, shifting winds and often by heavy, short-lived squalls (Roberts et al. 1987), and at our site by a rapid drop in water levels (Fig. 8 and 9). After the front passes, strong northerly winds, which characterize the post-frontal stage, drive water levels down in coastal embayments (Roberts et al. 1987), and result in dampened tidal amplitude in the postfrontal period (Fig. 8 and 9). During the pre-frontal stage, water levels rise at the bayou mouth, accompanied by elevated concentrations of TSS in incoming waters. The passage of the front brings a rapid drop in water levels and a period of outflow from the bayou that is longer than the typical ebb tide. Suspended sediment concentrations are lower during the post-frontal stage than during the prefrontal stage, particularly in incoming waters. Although the postfrontal stage frequently brings strong winds, these winds are out of the north rather than the southeast or southwest like prefrontal winds. The location of our site on the northern shoreline of Live Oak Bay may result in lower concentration of TSS during the postfrontal stage at our site than would be typical of sites oriented differently. However, net flux would be greatly reduced during postfrontal conditions regardless of the orientation of the site due to the lowered water levels and dampened tides resulting from strong north winds. The dampening effect of the postfrontal stage on the tide at our site is evident in both the October and February data (Fig. 8 and 9).

The October cold front resulted in net TSS flux less than estimated error in our measurements, while the February front resulted in a large net inland flux. The difference in the two fronts can be seen in Fig. 8 and 9; TSS concentrations during the October event remain elevated during the large drop in water level and accompanying outflow in the bayou that characterize the frontal passage stage. In contrast, TSS concentration is relatively low during the frontal passage stage of the February event. The effect of high TSS concentration during the October frontal passage outflow is that much of the TSS imported during the prefrontal stage is removed from the marsh and net flux is small for the event. Although both of these frontal passages produced locally heavy rains in coastal Louisiana, (Louisiana Office of State Climatology 1995, 1996) the difference in the two events may be due to differences in the rainfall produced at our site. Higher rainfall during the October front may be responsible for elevated TSS concentrations in the bayou during the frontal passage stage of the October event. However, rainfall was not measured at our site, so the effects of rainfall differences is speculative. Overall, the response of the bayou to the two events is very similar. The prefrontal stage is much longer during each of the two events than is the frontal passage stage, and this extended period of sediment import into the bayou appears to be the dominant feature of frontal passages; the quantity of sediment imported during the prefrontal stage is as large as or larger than the quantity exported during the frontal passage. This supports the conclusion that numerous cold frontal passages will result in a large net import of sediment to the bayou over the course of the winter.

Baumann et al. (1984) found that, in the absence of tropical storm activity, most sediment deposition occurred during the winter months at their Barataria Bay salt marsh study site. Reed (1989) confirmed that storms resulting from the passage of cold fronts through the region result in the majority of marsh surface sedimentation during the winter. This effect was attributed to the combination of wind driven surface waves, which resuspend bay bottom sediments, and high water levels, which carry sediments onto the marsh surface and permit deposition to occur. Our findings that landward sediment flux results from cold front passages is in agreement with these earlier findings. However, during our study, most cold front passages, including both of the fronts during which we measured TSS flux, did not produce storm surges large enough to significantly flood the marsh surface. Of the 25 frontal passages evident in our records of water level at Ugly Shack Bayou during the winter of 1995/1996 only four fronts produced water levels higher than marsh surface level, and none of the fronts included water levels more than 20 cm higher than the marsh surface. This indicates that although sediment was imported to the bayou during these passages, the majority of this sediment was deposited within the bayou and low lying parts of the marsh, and that most of the vegetated marsh was not able to receive this sediment. In this respect, winter cold front passages differ from fall storms, which are discussed below.

Another type of storm event that appears to be typical of coastal Louisiana was identified by this study. These late summer storms consist of strong, persistent winds with an easterly component that result in suspension of bay bottom sediments and a large rise in estuarine water levels of up to 1 m at our site (Table 4); the late summer and fall storms during 1996 consisted only of wind and did not result in rain, thunderstorms, or other severe weather that are typically associated with storms. Southeast winds which dominate summer conditions in Louisiana area associated with the "Mexican heat low" centered over Texas (Baumann 1987). The occurrence of late summer storms coincides with a rise in water levels throughout the northern Gulf of Mexico (Fig. 2) resulting in marshes at our site being inundated with far greater frequency during late summer than at other times of the year (Fig. 2). The large number of late summer storms during 1996 is associated with the relatively high water levels recorded at the study site during summer and fall 1996 (Fig. 2), and is responsible for the larger than normal range of water level fluctuations observed that year.

The dominant force creating the consistent annual rise and fall of water level in the northern Gulf of Mexico (Fig. 2) is the seasonal change in water volume in the Gulf that results from cooling and heating of nearshore waters. The secondary high water peak occurring in early summer and the low in mid summer have been attributed to wind stresses (Baumann 1987). Baumann (1980) showed that the late summer peak in water levels is much more pronounced than the early summer peak in southerly portions of the Barataria Basin. The high water peak occurring in late summer appears to be the more dominant one at our site, resulting in increased occurrence of marsh surface inundation during July through October. There appears to be significant inter-annual variability, which is evident in the data from the site

(Fig. 2 and 11), and during certain summers, high water conditions may persist from May or June through October as occurred during 1996 (Fig. 2).

Late summer storms are represented in our sediment flux measurements by the passage of a tropical depression (which later became T.S. Dean) to the south of Barataria Basin during late July and early August 1995 which resulted in a typical storm surge (Fig. 10). T.S. Dean produced a large net inland flux of suspended sediment, and the high water levels during the event suggest that marsh surfaces received much of the sediments. Rising water levels and vigorous wave action in Live Oak Bay and adjacent Hackberry Bay during the early stages of the storm surge resulted in high concentrations of suspended sediments in incoming water. Water levels remained high for several days allowing sediments to settle out of the water before it moved off of the marsh. Thus, the duration of the storm surge is an important contributor to its sedimentation effects. Figure 10 indicates that within approximately 25 hours of the peak water level suspended sediment concentrations in Ugly Shack Bayou had returned to near pre-storm levels, suggesting that a storm surge that lasts at least 25 hours will result in as large a net sediment flux as an event of longer duration. Each of the five events described in Table 4 included storm surges of far more than 25 hours duration. This supports the assumption that each of the events had the potential to result in large sediment imports to the bayou.

The estimated sediment input resulting from late summer storms, 140,000 kg TSS year^{-1} is of similar magnitude to the 262,500 kg TSS estimated to be imported by cold front passages each winter, and indicates that late summer storms may be an important component in the annual sediment budget of the study site second only to winter cold fronts in importing sediments to tidal marshes. An important difference between late summer storms and winter cold fronts is that late summer storms result in almost complete flooding of tidal marshes and permit sediment deposition in all parts of the marsh, while cold fronts typically flood only the lowest elevation portions of the vegetated marsh surface and do not allow sediment deposition in all parts of the marsh. For this reason, late summer storms may be the largest contributors to sedimentation in vegetated portions of the marsh at our site.

Baumann et al. (1984) found that tropical storm activity has the potential to exert a major influence on annual sedimentation rates in Barataria Bay marshes. They reasoned, however, that the low frequency of tropical storms (12% chance annually of passage of a hurricane within 80 km) makes their influence less important than that of the much more numerous cold front passages (25 yr^{-1}). Our results demonstrate that the close passage of a tropical storm is not necessary to create a storm surge that has a significant influence on sediment dynamics in tidal marsh systems; the distant passage of a tropical depression or wind resulting from a strong pressure gradient in the northern Gulf of Mexico can create important storm surges. Thus, tropical depressions and other storms have a significant influence on sedimentation despite the low frequency of hurricane impact on the estuary.

A third type of storm that may have a potentially large influence on the sediment dynamics of tidal marshes is thunderstorms. Rainfall on exposed marsh surfaces can result in erosion of surficial marsh sediments and their removal from the marsh in runoff waters (Ward 1981; Wolaver et al. 1988; Roman and Daiber 1989). Summer is characterized by frequent convective thunderstorms caused by local surface heating and convective updrafts (Baumann 1987). Rainfall is most frequent during summer (Table 5) as indicated by the higher number of rain days during June

Table 5. Monthly Average Wind Speed and Rainfall During Study

Month	Average wind speed[a] (m/s)	Rain Days[b]	Rainfall[b] (in)	Average Rainfall (in)
June 1995	4.29	7.8	3.86	4.85
July 1995	4.88	13.4	7.43	6.60
August 1995	3.69	11.5	5.03	5.95
September 1995	4.38	4.7	2.12	5.95
October 1995	6.66	6.8	2.95	3.29
November 1995	5.89	8.3	5.47	4.22
December 1995	5.90	8.2	3.88	5.25
January 1996	6.08	8.9	3.95	4.94
February 1996	5.64	4.1	2.28	5.66
March 1996	6.21	6.3	3.94	4.96
April 1996	5.80	5.7	4.14	4.17
May 1996	4.42	4.8	1.74	4.84
June 1996	3.55	13.0	6.95	4.85
July 1996	3.83	13.0	7.64	6.60
August 1996	3.79	16.2	6.91	5.95
September 1996	4.24	12.6	5.85	5.95
October 1996	7.09	6.7	1.90	3.29

[a]Wind speed measured at Grand Isle, LA by National Oceanic and Atmospheric Administration (N.O.A.A)
[b]Average of all southeastern LA stations reported by the Southern Regional Climate Center, 1995 and 1996.

through September (10.1 days $month^{-1}$) as compared to other months (6.6 days $month^{-1}$). Our measurements of TSS and runoff during and after a thunderstorm that occurred while the marsh surface was exposed indicate that substantial TSS was removed from the marsh by this event. Convective thunderstorm activity occurs on a small scale and, despite the potential for high wind velocities, does not significantly influence water levels in Barataria Bay. Therefore, the effects of thunderstorms on sediment dynamics in the estuary is erosion of marsh surface sediments and their transport off of marsh surfaces by storm runoff.

The thunderstorm during which sediment discharge was measured on September 20, 1996 resulted in the removal of 228 kg TSS from the small watershed that was gaged. This is equivalent to a discharge of 16,200 kg TSS from the marsh surface into Ugly Shack Bayou. While this is not directly comparable to discharge passing the gaging platform at the mouth of Ugly Shack Bayou, it illustrates the large influence a thunderstorm can have on sediment dynamics of the bayou, and suggests that the numerous thunderstorms that occur each summer, as well as the heavy rains that accompany cold front passage during the winter months, may play a large role in sediment dynamics of the marshes by eroding sediments from the marsh and transporting them to the bayou, where they can then be removed from the bayou by tidal currents.

Calm Weather TSS Flux

Our measurements of suspended sediment flux during June and July 1995 indicate that during the summer, normal tidal action results in a net export of suspended sediments from Ugly Shack Bayou due to consistently higher concentrations of TSS during ebb tides than during flood tides. This consistent difference is particularly evident during the June tidal cycle (Fig. 7) but occurred also during the July sampling period (Table 2). The summer export of sediment from the bayou may be explained by several factors which have been demonstrated to influence sediment flux. Rainfall such as thunderstorms on the exposed marsh will result in sediment export as discussed above. Marsh surface was exposed throughout the month of June 1995 (Fig. 2), and, although the number of rain days was below the annual average (Table 5), the almost constant exposure of the marsh surface insures that the rain that occurred fell on the exposed marsh. Rainfall has been demonstrated to influence net sediment flux in tidal channels for at least two tidal cycles after the rain (Roman and Daiber 1989). This suggests that the 6 to 7 rain days estimated to have occurred at the site during June 1995 would have influenced sediment flux throughout much of the month.

Several authors have suggested that biological activity, especially burrowing activity by small, marsh-dwelling crabs, contributes to summer turbidity by softening sediments and by resuspending sediments (Stevenson et al. 1988). Small crabs are extremely abundant on marshes at our study site, and are primarily active during the summer months, and their activity probably contributes to erosion of marsh sediments during summer months. While TSS values are generally lower during summer than during winter, the difference between ebb TSS and flood TSS is greater during June and July than during October or February, possibly reflecting both increased burrowing activity by crabs and more frequent thunderstorms during summer months.

Net export of sediments is facilitated by high concentrations of suspended sediments in flooding water (Leonard et al. 1995), while low concentrations of TSS in incoming water would favor net export of sediments. Export of TSS observed in the bayou during tidal cycles in June and July 1995 may be partially explained by the occurrence of calmer winds (Table 5) and more stable weather conditions (Baumann 1987) during summer months than during winter. Calmer conditions result in low concentrations of suspended sediments in the bay and thus, a low supply of sediment to the bayou/marsh. In addition, little or no sediment is transported from the upper basin to the lower basin during summer, thus depriving lower basin waters of a source of sediments that is present at other seasons (Garrepally 1996). Our data (Fig. 4) follow the results of Cruz-Orozco (1971) who found that suspended sediment concentrations in open water bodies of Barataria Basin are lower during summer than during winter. Our study found lower TSS in incoming waters during the summer sampling periods (June and July) as compared to the winter periods (October and February) (Table 2). This contributes to a net outward flow of suspended sediments during summer by resulting in low concentrations of suspended sediments during flood tides as compared to ebb tides.

The October 1995 sampling period was the only calm weather period during which a net inland flux of TSS was observed. October is the month with the lowest average rainfall (Table 5), and is also a month during which water levels are generally high and marsh surface inundation occurs frequently (Fig. 2). This inundation protects marsh surfaces from the erosional effects of rainfall. In addition to reducing the potential for rainfall to erode marsh surface sediments, inundation of the marsh surface allows sediment to be deposited on vegetated marsh surfaces, removing the sediment from bayou waters and shifting the balance toward net import of sediments in the bayou. October, the only month during which net sediment import was observed during regular tidal action, was also the month with the highest rate of marsh inundation among the months sampled. Although August 1995 saw similar overall rate of marsh surface inundation, much of the inundation occurred during the passage of T.S. Dean, and the reported rate is not indicative of typical conditions through the month (Fig. 2). Roman and Daiber (1989) found that a hard rain on the surface of the marsh can influence net sediment flux for at least two tidal cycles after the rain, which suggests that a deposition event such as a period of marsh inundation could also influence net sediment flux for several tidal cycles. Thus, sediment flux throughout October could be influenced by the periodic flooding of the marsh surface and resultant sediment deposition.

Flooding of the marsh has a potentially large effect on sediment flux for two reasons. First, the flooded marsh has a much larger surface area than the bayou and therefore provides a larger area for sediment deposition. This larger area also results in lower water velocities than occur in the bayou permitting suspended sediments to settle to the marsh surface under relatively quiescent conditions (Boto and Patrick

1978). Second, the vegetation of the marsh facilitates removal from flooding waters of particles theoretically too fine to settle during a typical tidal cycle (Stumpf 1983).

A final point that explains the net import of TSS observed during October is that suspended sediment concentrations are higher during winter months (including October) (Cruz-Orozco 1971) providing a source of suspended sediments with incoming waters during flood tides. October inflow TSS values are higher than June or July values (Table 2).

During February, net flux is less than estimated error of the estimate, and does not show the sediment import measured during the other winter calm-weather sampling period. Water levels are much lower during February than during October, and astronomical tides do not approach the surface of the marshes. This eliminates the marsh surface as a potential sediment sink. Rainfall is higher during February (Table 5), which coupled with a high rate of marsh surface exposure (Fig. 2) allows sediment to be eroded from the marsh surface and transported to the bayou, contributing to net export of sediment. Thus, although inflow TSS is higher during February than during October, the absence of the marsh surface as a sediment sink and the supply of rain-eroded surficial sediments to the bayou result in a flux of sediments less than the estimated error of measurement rather than a measurable import.

<u>Annual Sediment Import</u>

The TSS flux in Ugly Shack Bayou measured here represents a measurement of net sedimentation to the marshes surrounding the bayou. Other published measurements of net sedimentation made in Louisiana were based on measurements of sediment deposited on marsh surfaces. Although the two methods of measurement examine similar processes, measurements made by one method are not directly comparable to those made by the other. None the less, our measurements of net sediment flux are compared in the following paragraphs to published measurements of marsh surface deposition; the comparison will be used to demonstrate that measurements presented here are of the same magnitude as previous measurements and to examine conditions observed during this study as influences on sedimentation. This comparison is not meant to suggest that the sediment observed passing the Ugly Shack Bayou gaging station is believed to have been evenly distributed on the surface of the marshes surrounding the bayou. The distribution of deposited sediments will be discussed below.

Long-term sediment accretion rates in Louisiana tidal marshes in or near the Barataria Basin range from 1.3 cm year^{-1} in streamside marshes and 0.7 cm year^{-1} in more inland marshes (Hatton et al. 1983), 1.35 cm year^{-1} in streamside marshes and 0.75 cm year^{-1} in more inland marshes (Baumann et al. 1984), to 0.78 to 0.42 cm year^{-1} (DeLaune et al. 1989). The drainage area of Ugly Shack Bayou includes much more inland marsh than streamside marsh, so based on the above estimates an average sedimentation rate of approximately 0.75 cm year^{-1} is expected.

The suspended sediments collected in Ugly Shack Bayou consist of approximately 25% VSS, and are thus similar to marsh sediments found by DeLaune et al. (1989) at two sites in salt marshes of southwestern Barataria Basin. In-situ production of organic matter in salt marshes contributes to marsh accretion by contributing organic matter to the marsh surface (DeLaune et al. 1990; Nyman et al. 1990), and this process undoubtedly occurs at the study site. The volatile portion of the TSS imported to Ugly Shack Bay may be degraded after the sediment is deposited on the marsh surface and replaced by organic matter produced in-situ, but the ratio of VSS/TSS does not change. Thus, for the purpose of comparison with previous measurements of marsh surface sedimentation, the quantity of TSS transported into the bayou can be translated into sediment accreted on the marsh surface. Our estimated average sediment import of 0.24 cm year^{-1} is less than half of the rate measured by previous researchers. Measurements of sediment accretion in marshes elsewhere in Louisiana include a measured rate of less than 0.1 cm year^{-1} at an Atchafalaya Bay marsh (Rejmanek et al. 1988) indicating that our estimate falls within the range of previously measured values for Louisiana marshes. Baumann et al. (1984) found that in years during which hurricanes did not influence their site, sediment accretion averaged 1.1 cm year^{-1} streamside and 0.6 cm year^{-1} inland, while during hurricane years the rates rose to 1.5 and 0.9 cm year^{-1}. Similarly Rejmanek et al. (1988) found that sedimentation of <0.1 cm year^{-1} occurred during years without hurricane impacts, while two hurricane passages resulted in accretion of >2.2 cm accumulation in one summer season. This suggests that our low estimates of sediment accretion may be explained by the lack of hurricane or strong tropical storm impacts in our data, and that long term sediment accretion rates reflect the influences of these storms.

The preceding comparisons are not meant to suggest that TSS passing the Ugly Shack Bayou gaging station are believed to have been distributed evenly across the marsh surface; water levels throughout much of the study period were below the level of the marsh surface indicating that most sediment was at least temporarily deposited in the bayou channel and in low lying portions of the marsh surface. The Ugly Shack Bayou drainage area of 710,000 m^2 was estimated based on the area of marsh from which water would be expected to drain toward the bayou. This area is frequently not fully flooded during periods of sediment import, including many of the cold fronts which passed during this study and which imported a large portion of the total net sediment imported during this study. Thus, the effective drainage area of the bayou available for sediment deposition will be less than the total estimated drainage area. The relatively low estimates of net sediment import, compared to published estimates, that are reported here may be due to the exaggerated estimate of bayou drainage area; the area in which most sediment is deposited is smaller than the total drainage area of the bayou and resulting deposition rates are higher than estimated.

Cold front passages are the largest source of sediments to marshes during years without tropical storm or hurricane activity (Baumann et al. 1984; Reed 1989). This is true at our site, where cold fronts supplied the largest portion of the annual sediment influx (Fig. 12). The number of cold fronts observed at our site is typical of normal winter conditions based on predictions of cold front frequency (Roberts et al. 1989; Moeller et al. 1993).

Apparent sea level rise, resulting from both actual sea level rise and land subsidence, is occurring at a rate of about 1.23 cm $year^{-1}$ in Barataria Bay marshes (Baumann et al. 1984). Thus, marshes at our study site are not keeping pace with apparent sea level rise, a characteristic of deteriorating marshes in Louisiana (Baumann et al. 1984). This finding matches the findings of other researchers (Hatton et al. 1983; Baumann et al. 1984; DeLaune et al. 1989); marshes in portions of the coastal zone that are not impacted by Mississippi River sediment inputs are not keeping pace with apparent sea level rise and are deteriorating in Louisiana.

Sediment Dynamics in Ugly Shack Bayou and Live Oak Bay

This section of the discussion will examine the relationships between sediment dynamics in Ugly Shack Bayou and the surrounding salt marshes with sediment dynamics of Live Oak Bay.

Sediment Deposition and Burial

Short-term mass deposition data at the Live Oak Bay station indicate that September through April is the most active season for sediment deposition (Fig. 6). Greater than 70% of the total sediment deposited during the first twelve months of this study was deposited between September and April; the surface bottom sediment ^{7}Be inventory data indicate that sediment was transported to the site, on a net basis, for all of these months. New inventory and atmospheric input data during the same period indicate that bottom surface sediment ^{7}Be inventories always exceeded the atmospheric supply. This suggests that sediments were resuspended and transported (focused) to the Live Oak Bay site (Fig. 5). In contrast, the summer season, April through August, appear to result in net sediment redistribution, with transport away from the study site reflected by new inventories in the bottom sediments during this time period that are lower than the atmospheric input to the station (Fig. 5). A third set of circumstances appears during August through September, and is repeated again in September through October 1996 (Booth 1997) when high deposition, coupled with new ^{7}Be inventories lower than atmospheric input, reflects the influence of storms. The study site receives substantial net sediment inputs, but considerable sediment is transported into bayous and marshes inland of the bay bottom site.

The seasonal pattern of sediment dynamics observed here corresponds to the patterns of sediment transport from the upper basin (Garrepally 1996), and suggests that the upper basin is an important source of sediments to Live Oak Bay. During winter months of October through April winds are higher in the Barataria Basin than during summer months (Table 5), which is typical of weather conditions in the Barataria Basin (Cruz-Orozco 1971) and weather is generally less stable than during summer (Baumann 1987). Cruz-Orozco (1971) found that wind speed is correlated with increased levels of TSS in Barataria Basin waters and that suspended sediment concentrations in open water bodies of Barataria Basin are higher during winter than during summer. This finding agrees with our results, which show that suspended sediment concentrations in Live Oak Bay average higher during winter than during summer (Fig. 4). Sediment resuspension has the potential to result in either sediment removal from a site, if resuspended sediments are transported away, or to result in sediment accretion if suspended sediments are focused toward a site. The high rates of sediment deposition observed during winter suggest that our site is a focus of sediment deposition and is not subject to extensive resuspension by winter wind driven waves. Our bay bottom sampling site lies in a small cove, and is often observed to be subject to much less choppy conditions than prevail in Live Oak Bay or adjacent Hackberry Bay. It appears that sediments resuspended elsewhere are transported to our site where they settle to the bottom under the relatively quiescent conditions. Suspended sediment is transported from the upper basin to the middle and lower portions of the basin during the winter (Garrepally 1996). This indicates that sediment can be transported over long distances in the Barataria, and that the source of our sediments may be as distant as the upper portions of the basin.

The proximity of the sampling site to the mouth of Ugly Shack Bayou provides an opportunity for sediment exported from the bayou or from the marsh via the bayou to be deposited at the bay bottom sampling site. However, during the winter, significant net fluxes of TSS in the bayou are directed inland during both stormy and calm conditions. This indicates that the bayou/marsh are not the source of the deposited sediment observed at the bay bottom site during winter months. On the other hand, the net accumulation of sediments at the bay bottom site suggests that sediments moving into the bayou during the winter are not eroded from nearby bottom materials, but rather are transported to the bayou from a more distant source. Thus both nearshore bay bottoms and coastal marshes are sinks for sediments and carbon during the winter months.

Summer's calmer, more stable conditions (Table 5) correspond to lowered rates of deposition at the bay bottom sampling site. Lower concentrations of suspended sediments in Live Oak Bay suggest that resuspension of bay bottom sediments, one apparent source of winter-deposited sediments, is less active during summer than during winter. Sediment transport from the upper to the lower and middle parts of the Barataria Basin is lower during summer than at other times of the year (Garrepally 1996), providing an additional explanation for low summer TSS values. New ^{7}Be inventories lower than atmospheric inputs reveal an apparent movement of sediments away from the sampling site during the summer. This suggests that sediment resuspension in the shallow, nearshore waters of our sampling site exceeds the input of sediments both from deeper, central sections of the estuary and inputs from the bayou/marsh. Ugly Shack Bayou is a net exporter of suspended sediments during the summer while at the same time there is a net loss of sediments or a small net gain at the bay bottom site. Thus, sediments exported from the bayou are transported away from the immediate outfall of the bayou into other sections of the estuary. This suggests that tidal marshes are net sources of carbon and sediments to estuarine waters during the summer months.

During Fall 1996 (August - October), relatively high water levels (Fig. 2) and numerous wind-driven storm surges define a third "season," or set of conditions, that produced a unique sedimentary response. The event that produced the largest net flux of TSS in Ugly Shack Bayou during this study was the passage of a tropical depression, which later became T.S. Dean, through the central Gulf of Mexico to the south of our study site during late July and early August 1995. This storm produced a large net inland flux of suspended sediment equivalent to more than 30 times the largest net flux recorded during calm conditions and more than twice the magnitude of the second largest event recorded (Tables 2 and 3).

Although our measurements of bay bottom sedimentation had not yet begun at the time that T.S. Dean passed the site, several similar events occurred at the site during late Summer 1996, after TSS flux measurement had ceased. A comparison of relevant physical measurements during each of these five events and during the passage of T.S. Dean is shown in Table 4, and demonstrates that T.S. Dean was fairly typical of the events that occurred during September and October 1996. At the bay bottom site, the measurement periods August 1996 through September 1996 and September through October 1996 (Booth 1997) include the effects of several wind events similar to the passage of T.S. Dean and demonstrate that these events produced a unique response in the bay bottom sedimentation record. Each of these periods saw high sediment deposition coupled with new ^{7}Be inventories less than atmospheric inputs, a situation that is not seen at other times during this study. These characteristics: high wind events, high rates of mass deposition, new ^{7}Be inventories less than atmospheric inputs, and large inland fluxes of TSS (expected based on the similarity of these events with the passage of T.S. Dean) suggest the following explanation. Mass deposition rates in Live Oak Bay are high during this season. However, new ^{7}Be inventories are below atmospheric inputs, suggesting sediment movement away from the site. This apparent conflict is explained by large storm surges and strong waves, combined with the seasonally high water levels (Fig. 2), which result in resuspension of bay bottom sediments and movement of considerable sediment onto marsh surfaces. The ^{7}Be input during these events is distributed among all of the suspended sediments in the water column during the event. Similarly, ^{7}Be held by near surface sediments may be resuspended and distributed throughout the water column. This suspended sediment is then deposited in part on the bay bottom and in part farther inland in the bayou and marshes. Thus, although the bay bottom may receive a substantial input of sediments, some of the sediments, as well as some of the atmospheric ^{7}Be input, is transported into the bayou and marshes. The result is new ^{7}Be inventories less than atmospheric inputs and significant mass deposition. Fall conditions result in net sediment import to both the bay bottom and the bayou/marsh, indicating that the source of deposited sediments lies outside of Live Oak Bay. Measured sediment transport from the upper basin to lower basin remains low during the months of September and October (Garrepally 1996). However, the effects of fall storms may not have been adequately sampled, and the upper basin may have provided some of the sediments that were transported to our site during the Fall season.

Winter storm activity in Southeast Louisiana is largely the result of the passage of cold fronts and cold air outbreaks. These events have significant sedimentological and geomorphic impacts on Louisiana coastal environments which are magnified by the consistent succession of winds, waves, and water levels that occurs with cold front passage (Roberts et al. 1987). Baumann et al. (1984) found that, in the absence of tropical storm activity, most sediment deposition occurred during the winter months at their Barataria Bay salt marsh study site. Reed (1989) confirmed that storms resulting from the passage of cold fronts through the region result in the majority of marsh surface sedimentation during the winter. This effect was attributed to the combination of waves in open waters created by high winds, which resuspend bay bottom sediments, and high water levels, which carry sediments onto the marsh surface and allow deposition to occur. Our results indicate that winter is the time of greatest sediment movement in and around Live Oak Bay. Greater than 70% of the sediment deposition on the bay bottom during this study occurred during the winter months. Winter is also the season of the stormiest weather at the site, with cold-front passages occurring 25 times during the winter of 1995/1996, and approximately 30 times each winter season (Moeller et al. 1993). Although the sediment flux resulting from our two measured cold front passages varies greatly (Table 3), the consistent pattern of conditions that result from passage of fronts insures that the average contribution of cold front passages is a net inland flux of TSS. The frequency of cold frontal passage makes their summed effect potentially great. Although our sampling of two cold fronts is not sufficient to accurately estimate the magnitude of their effects on bayou TSS flux or any variability of their effects through the course of a winter season, the sediment record from the bay bottom site suggests that there is a consistent movement of sediments into Live Oak Bay throughout the winter and that the effects of cold fronts do not vary greatly through the winter.

Estuarine Sediment Dynamics Model

The various data presented here make possible the construction of an overall model of sediment dynamics in the bay/bayou/marsh system. Our data suggest that the year be divided into three seasons: Winter (October-April), Summer (April-July), and Fall (variable in length and occurrence). The months of August through October are transition months which, under the right circumstances, can be defined as a third season Fall. The timings of the three seasons are variable and are based on hydrologic phenomena which will be explained below. It should be noted that seasons as defined here represent sets of climatic and hydrologic conditions rather than distinct dates on a calendar. The duration and timing of the three seasons may vary greatly from year to year.

The winter season is characterized by the frequent passage of cold fronts; initiation of cold front passage is typically during October. Frequent storms and windy conditions result in high suspended sediment concentrations in estuarine waters. Sediment deposition is high in Live Oak Bay; ^{7}Be inventories in excess of atmospheric ^{7}Be inputs indicate that sediment is focused into Live Oak Bay. Both tidal currents and frontal passage result in significant fluxes of suspended sediments being directed inland in Ugly Shack Bayou. Both bay bottoms and tidal bayous and marshes act as sediment sinks during the winter.

The summer season generally begins in late April or May with the cessation of cold front passage, and is characterized by calm weather conditions and by water levels higher than winter levels (Fig. 2). The calm weather (Table 5) results in low

TSS concentrations in estuarine waters; this effect is amplified by high water levels which are associated with lower levels of TSS (Cruz-Orozco 1971) and with reduced transport of sediments from upper sections of the estuary (Garrepally 1996). Mass deposition rates in Live Oak Bay are low, and ^{7}Be inventories below atmospheric inputs indicate that sediment is moved out of Live Oak Bay. Tidal action results in net sediment export from Ugly Shack Bayou, and sediments and carbon are transported beyond the bay bottom sampling site out into the estuary. Tidal bayous and marshes act as sources of sediments and carbon for the estuary during summer, while relatively little deposition occurs on the bay bottom. An exception to the general trend of sediment removal are occasional tropical storms during summer that result in large sediment inputs to bay bottoms and bayous and marshes.

The Fall season is defined by high sustained winds and storm surges and is a season of large sediment flux into tidal bayous and marshes. Substantial deposition of sediments on the bay bottom can occur, although ^{7}Be inventories indicate that considerable sediment is transported out of the bay into bayous and marshes. Our data indicate that Fall, as defined here, does not occur annually at our study site. Fall conditions were not prevalent during 1995 due to relatively low water levels (Fig. 2). In contrast 1996 saw relatively high water levels (Fig. 2), extended periods of high winds (Table 4), and frequent wind-driven storm surges, producing a distinct Fall signature in the sediment record (Fig. 5).

CONCLUSIONS

Flux of suspended sediment between an open bay and tidal marshes through a small bayou were measured periodically throughout all seasons of the year. Sampling occurred between June 1995 and February 1996; related data were gathered throughout the study period of April 1995 through October 1996. Long-term water level records indicate that the years 1995 and 1996 were years of higher than average seasonal water level fluctuations. Water level fluctuations during the study period followed typical trends and were within the range of observed values until October 1996, when high water levels resulted in the largest seasonal water level fluctuations observed during a fifteen year period.

The flux of suspended sediments through a tidal bayou in the Barataria Bay estuary is dominated by the effects of storms. Winter cold front passages, which occur approximately 25 times per year between October and April, are the largest contributor to sediment import in the bayou. The transport of sediments from the upper basin to the lower basin combined wind driven waves and storm surges result in net sediment import during cold fronts. The large number of cold fronts magnifies the effects of an individual front and creates a large cumulative impact on sediment dynamics. Late summer storms, which individually import more sediment than a single cold front passage, also result in significant import of sediment to the bayou. The combined effects of these storms is a large net import of sediment to the bayou. Typical calm-weather tidally-driven flows in the bayou result in sediment export in most seasons, but this export is less than the import resulting from storms, and sediment is imported to the bayou/marsh on an annual basis. A variety of factors influence net sediment flux in the bayou including flooding of the marsh surface, rainfall on the exposed marsh, and winds and resulting sediment suspension in adjacent Live Oak Bay, and transport of sediments from fresh and brackish portions of the Barataria Estuary. Annual rates of sediment import to the bayou are shown to be comparable to rates determined from measurements of sediment accretion on marsh surfaces in earlier studies. Slightly lower rates of sediment import found here may indicate the effects of hurricanes on longer-term sedimentation measurements.

Sediment deposition at a site on the bottom of a shallow, saline embayment in the Barataria Bay Estuary (Live Oak Bay) and suspended sediment flux in an adjacent tidal bayou were monitored to examine the seasonal sediment dynamics of the system. Bay bottom sediment deposition was examined using ^{7}Be tracer technique, while sediment fluxes between open waters and the bayou and marsh were estimated by monitoring water flux and suspended sediment concentrations in the bayou. Results show that sediments, and particulate carbon which constitutes a portion of sediment, are transported to the site during winter, while the bayou exports sediments and carbon and the bay bottom receives relatively minor inputs during summer. This pattern of sediment transport coincides with sediment transport between the upper basin and middle and lower basin as measured by Garrepally (1996). During certain years, storms can produce a distinct Fall season and result in large inputs of sediments to the system. Sediment dynamics in the system are shown to be controlled primarily by weather; stormy conditions result in resuspension and redistribution of bay bottom sediments and transport of sediment from the upper basin, while calm summer weather permits erosion of marshes, and higher summer water levels result in little or no sediment transport from the upper basin to the lower basin. Similar sedimentary responses of the bay and bayou to weather conditions indicates that sediments are transported to the site from outside the immediate Live Oak Bay area; results suggest that the upper basin may be the source of much of the sediment deposited at the study site.

CHAPTER 4. POREWATER EXPORT FROM TIDAL MARSHES OF THE BARATARIA BAY ESTUARY, LOUISIANA, U.S.A.

INTRODUCTION

The export of nutrients and carbon compounds from tidal marshes to surface waters has long been hypothesized to play a major role in the productivity and nutrient cycles of estuarine ecosystems (Nixon 1980). In the past several decades, a large number of studies have aimed to quantify fluxes between marshes and open waters of materials in surface channels (Stevenson et al. 1988). Although the porewaters of salt marshes are known to be enriched in a variety of constituents compared to surface waters, few studies have examined the transfer of porewaters or their constituents between marshes and surface waters.

Several researchers have examined the seepage of porewater into tidal channels in salt marshes during periods when tidal fluctuations result in water level below the level of the marsh surface, and have generally found that significant horizontal movement of porewater is restricted to a narrow zone within approximately 15 m of the banks of tidal channels (Hemond and Fifield 1982; Agosta 1985; Yelverton and Hackney 1986; Nuttle 1988; Harvey et al. 1987). Although the narrow zone of dynamic porewater movement would seem to restrict porewater exchange and limit the effects of marshes on the chemistry of adjacent waters (Yelverton and Hackney 1986), other studies have shown that marshes can export significant amounts of constituents (Gardner 1975; Jordan and Correll 1985; Whiting et al. 1989).

Although horizontal movement of porewater has been demonstrated to occur only in a narrow zone near the banks of tidal creeks, a large portion of the marsh contributes to the export of porewater and porewater constituents due to diffusion of porewater constituents into a thin film of water on the surface of the drained marsh and the runoff of this water into surface rivulets (Gardner 1975; Wolaver et al. 1986; Wolaver and Spurrier 1988). Gardner (1975) demonstrated that the coastal marshes of South Carolina may export as much dissolved silica, phosphate, bicarbonate, and possibly ammonia as river export from the state, and thus, tidal marshes play an important role in the chemistry of nearshore marine waters in the state. On the other hand, Wolaver et al. (1986) and Wolaver and Spurrier (1988) examined carbon exchange between coastal waters and tidal marshes and decided that tidal marshes may not be a significant source of carbon to North Inlet, South Carolina.

Despite the large number of published studies of Louisiana's coastal marshes, research that directly examines porewater exports from marshes is lacking. A variety of researchers have estimated carbon or nutrient export from tidal marshes, based on carbon or nutrient budgets, but have not attempted to measure exports directly (e.g. Day et al. 1973; Happ et al. 1977; Madden and DeLaune; 1987). This study examines exports of porewater and porewater constituents from an intertidal salt marsh in the saline portion of the Barataria Bay Estuary, Louisiana. Runoff from the marsh during low-tide exposure of the marsh through a small rivulet on the marsh surface was measured, and the concentrations of various chemical constituents of the water were monitored in the rivulet, in surface waters, and in the marsh porewater to aid in the distinction of porewaters from surface waters in the rivulet. Estimates of horizontal subsurface seepage of porewater into the rivulet and the adjacent bayou are presented; seepage was shown to account for only a portion of the total export of porewater constituents. Additional export of constituents via diffusion into a shallow surface layer of water and runoff of this water is suggested as an important process contributing to constituent export.

STUDY AREA

The study site is an intertidal, salt marsh bordering a tidal bayou (Ugly Shack Bayou) that feeds into Live Oak Bay (Fig. 1). Live Oak Bay is a small embayment in the northwestern portion of Barataria Bay, a large saline embayment of the Barataria Bay Estuary that lies between the Mississippi River and Bayou Lafource along the Gulf of Mexico coast of southeast Louisiana. Ugly Shack Bayou is connected to the surrounding marsh by a system of shallow, narrow rivulets that range in size from approximately 2 m wide and 50 cm deep near the bayou, to channels less than 20 cm wide and 10 cm deep that eventually disappear into the marsh at the inland end of the system. These rivulets provide a means for porewater drainage from a large portion of the marsh interior that would otherwise be isolated from the bayou. The marsh surface is characterized by numerous shallow channels and puddles, many of which are connected in intricate patterns to form the surface drainage system that feeds the rivulets, while others are not directly connected to the drainage system. The smallest of these channels are heavily used by nutria and muskrats as runways through the marsh vegetation, and may originate as rodent runways that are enlarged partly by rodent traffic and partly by erosion by runoff water.

The presence of open, unvegetated areas in Louisiana marshes is associated with incipient marsh deterioration and land loss (Nyman et al. 1993). On our site, open areas are frequently connected to the system of rivulets that drain the marsh surface, and may form by widening of rivulet channels. Thus, the rivulet drainage system may be associated with marsh deterioration. High densities of muskrats are known to result in damage to tidal marshes due to excessive vegetation destruction by feeding muskrats (Abernathy 1987); the connection of muskrat runways with rivulet formation may constitute another connection between high muskrat populations and marsh deterioration

Vegetation at the site is primarily *Spartina alterniflora*, with smaller amounts of *Spartina patens* and *Distichlis spicata*, especially near the bayou, and *Juncus roemerianus*, particularly near rivulets and other shallow surface waters on the marsh. Marsh soils are generally high in organic matter and of high hydraulic conductivity, with occasional layers of clay or silt rich soils. The tidal range at the site is approximately 30 cm with one tidal cycle per day. Inundation and exposure of the marsh surface are unpredictable due to the strong influence of wind and barometric pressure changes on bay water levels; storm surges of up to 1 m are common at the site and may inundate marshes for several days. The average marsh surface elevation is approximately 15 cm above annual average water level.

A small rivulet, typical of many draining into Ugly Shack Bayou, was chosen for this study (Fig. 13). A gaging station was established on the lower reaches of the rivulet and two sets of well, equipped with water level gages and a recording datalogger, were installed at a lower and an upper station (Fig. 13). The drainage area of the rivulet, based on observed patterns of water flow and surface channel connections on the marsh, is approximately 10,000 m^2. A survey of the marsh surface indicates that a natural levee, raised approximately 30 to 40 cm over interior areas of the marsh and approximately 20 to 30 m wide borders Ugly Shack Bayou. Surface slopes on the marsh, excluding the natural levee, are approximately 0.003 m m^{-1}, or 0.3%.

METHODS

Field data collection for this study consisted of the continuous measurement of water levels in the marsh subsurface and rivulet from April 1996 until April 1997. Water level in the bayou was monitored as part of a larger study continuously from May 1995 until April 1997. Hydraulic conductivity of marsh soils was measured on June 18, 1996. Rivulet discharge was measured, and samples collected for chemical analyses, on September 20, 1996 and October 18, 1996. Additional rivulet discharge measurements were collected on November 26 and 27, 1996.

Hydraulic Conductivity

Hydraulic conductivity (K) of marsh soils was determined by the Auger-Hole Method as described by Bouwer and Jackson (1974). This method measures the rate of rise of water in a hole dug into the soil below the water line. A hole is made in

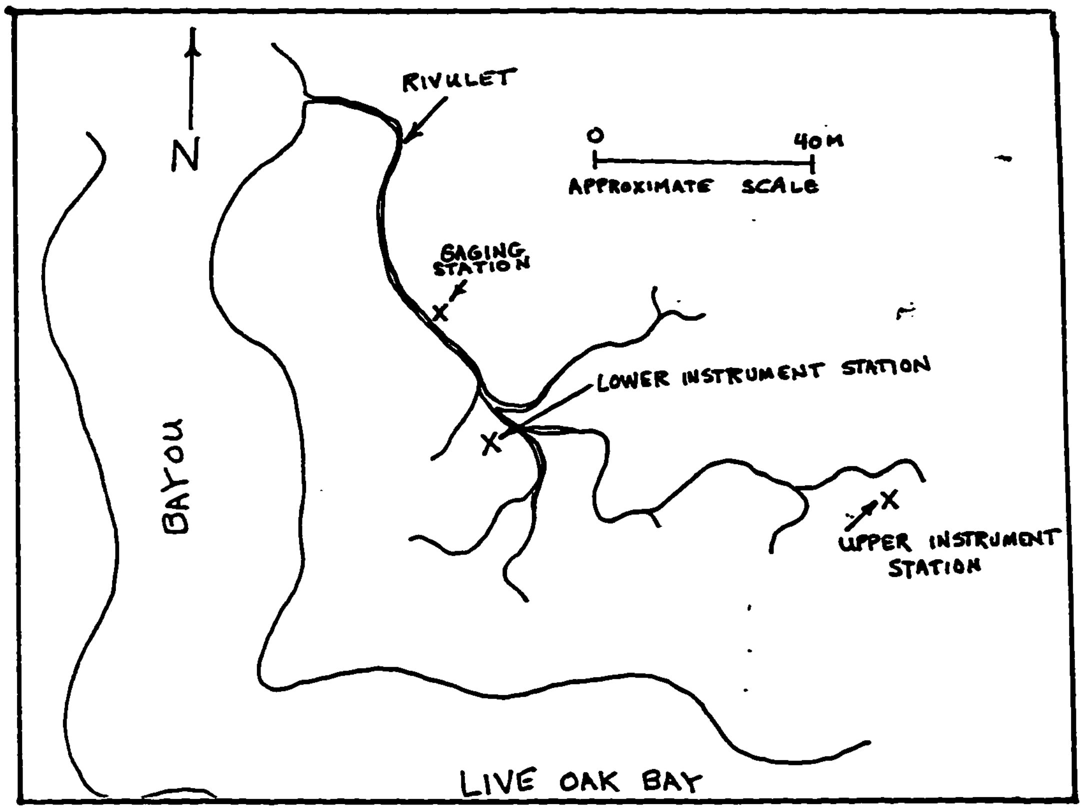


Figure 13. Study site diagram showing rivulet gaging station and instrument stations.

the soil, and water table position is established by allowing water level in the hole to equilibrate. Water is then bailed from the hole, drawdown of the water level in the hole is measured, and after bailing stops, the rate of rise of water in the hole is timed. The following equation is used to calculate K:

$$K = (233/Ht)*\log(y_o/y_t) \qquad (1)$$

where:

K = hydraulic conductivity (m/day)

t = time (min)

H = distance between water table and hole bottom (m)

y_o, y_t = distance between water table and water level in hole at time t = 0 and t, respectively (m)

This equation was developed using data obtained in the field and does not account for the diameter of the hole or position of an impermeable layer in the soil below the bottom of the hole, and it carries the inaccuracies of a field measurement such as nonuniformities in the soil and poor control of boundary conditions (Bouwer and Jackson 1974). Our measurements of K were made using holes of approximately 20 cm diameter and depth of approximately 30 cm. This upper zone of soil was measured because, based on drawdown measured in wells in the marsh and the depth of the channels of small rivulets on the marsh, most groundwater movement was believed to occur in the upper 30 cm of the soil. Two holes were constructed near the middle of the study watershed in typical interior marsh vegetated by *Spartina alterniflora*, and K was measured in each hole several times.

Watershed Area

The area of the watershed drained by the study rivulet was determined by measuring the boundary of the watershed area using a hand-held tape. Watershed boundaries were positioned based on observed directions of water movement and connections between surface channels in the marsh. The total length of rivulet connected to the drainage system under study was measured using a hand-held tape. Notations of the size of the rivulets measured were made to aid in the separation of rivulets typical of conditions at the lower station from rivulets more similar to the conditions at the upper station.

Rivulet Discharge

The discharge of water through the rivulet was gaged using a hand-held Marsh-McBirney electromagnetic current meter; discharge was measured at least every 30 min, with more frequent measurements taken during periods of rapid change in velocity or channel cross-sectional area. The width and depth of the rivulet were measured at the gaging station approximately every two hours or as necessary based on changes in water level and discharge. Current velocity was measured at mid-depth at each of three stations evenly spaced across the width of the rivulet. When width was less than approximately 50 cm velocity was measured only at the channel midpoint. The channel cross-section was divided into three sub-sections, with subarea divides falling midway between velocity measurement points. Total discharge was calculated as the sum of the products of each subsectional area and the corresponding measured velocity.

Water Table Fluctuations

Two stations were established on the marsh for monitoring water table fluctuations in the rivulet and in nearby marsh soils. The lower station is approximately 70 m from the mouth of the rivulet and 20 m upstream of the station where rivulet discharge was gaged. The upper station is located in a small rivulet near the upstream extent of the rivulet drainage system. The fluctuations of water levels in the rivulet and in the adjacent subsurface were monitored using Druck atmospherically-vented water level gages mounted inside PVC wells. Gage output was recorded by a Campbell Scientific CR10x datalogger mounted on a tripod above water level on the marsh. Wells were constructed of 2" ID PVC pipe slotted throughout its length and wrapped in a porous geotextile fabric to exclude soil particles from the inside of the wells. Observations in the field indicate that the fabric effectively excludes soil materials from the wells without measurably slowing water levels fluctuations in the well relative to outside water levels.

The lower station consists of three wells arranged in a transect running from the middle of the rivulet inland toward the interior section of the marsh. The first gage is located in the rivulet, the second 2 m from the rivulet edge, and the third 1.7 m from the second. Relative level of the gages could not be surveyed due to the uncertain position of the gages inside their wells. Relative positions of the gages were established based on periods when water level was known to be well above the marsh surface, and the level in all wells was assumed to be at the same level. The position of the gages relative to the marsh surface was established based on the water level fluctuations observed in the well. Water levels in all wells was identical while water level was above marsh surface level. As water level fell past the marsh surface level, water levels in the wells demonstrated a distinctive pattern of divergence as water level in the rivulet fell with bayou water level, but water level in the marsh soil fell more slowly; the more interior well revealed a slower drop in water level than the well closer to the rivulet (Fig. 14). This point of divergence was identified as the marsh surface level.

In order to assess the behavior of portions of the rivulet more distant from the bayou, two water level gages were installed in a small rivulet near the extreme upstream limits of the rivulet drainage system and at a point 2 m from the rivulet edge. Gages and wells used at the upper station are similar to those used at the main rivulet, and are connected to a similar datalogger.

Water Chemistry

Water samples were collected for analysis of a variety of chemical constituents from the rivulet, porewater, marsh surface, and from the bayou. Bayou and rivulet samples were collected every half hour with rivulet samples collected more frequently during rainfall. Marsh surface samples and porewater samples were collected at several locations in the watershed to provide an idea of the spatial variability of constituent concentrations, and porewater samples were collected at a variety of depths ranging from 5 to 85 cm. Surface and porewater samples were collected several times during each sampling trip, and more frequently during rainfall.

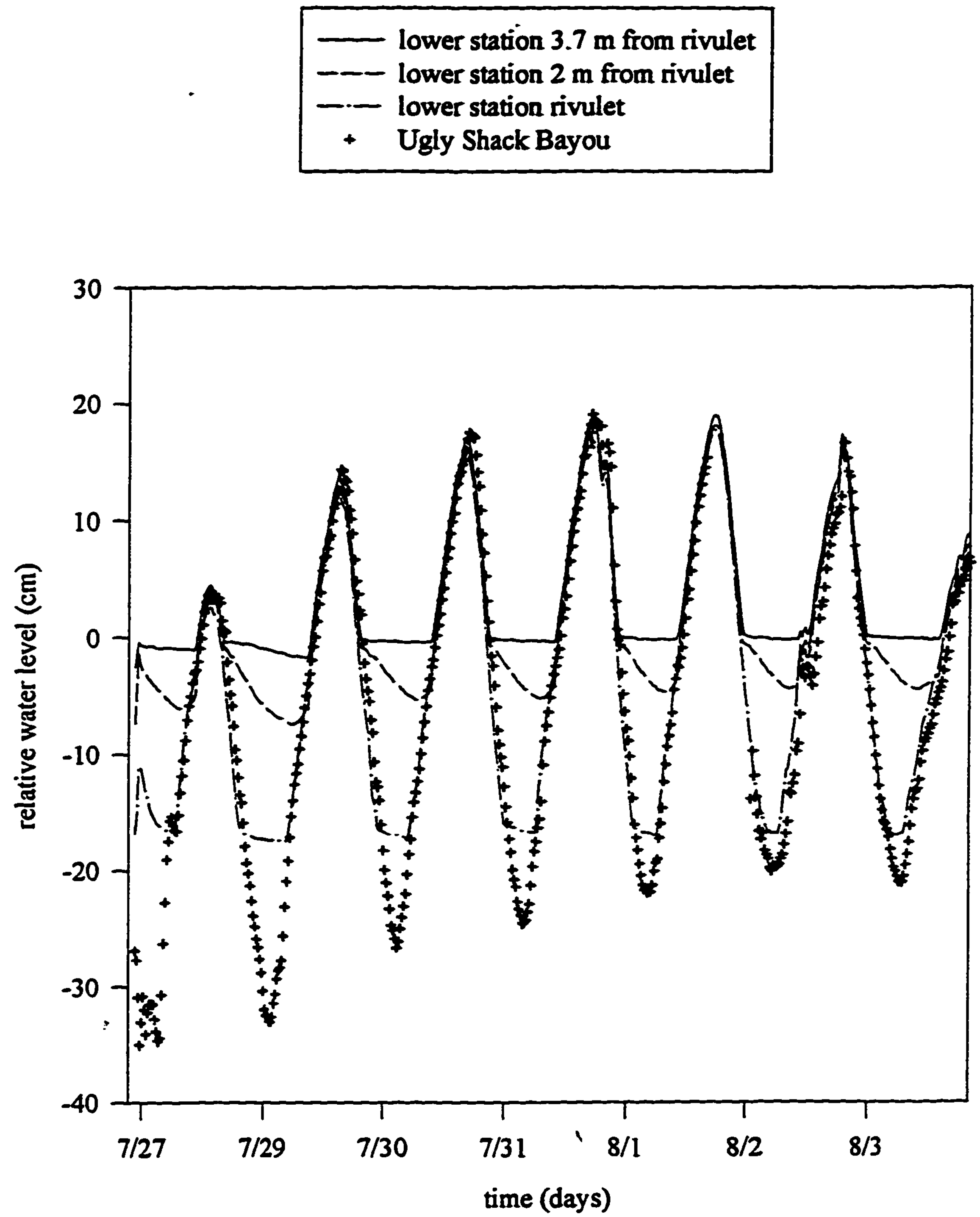


Figure 14. Water levels at lower rivulet station and in Ugly Shack Bayou relative to marsh surface level, July 27 through August 4,1996

Bayou and rivulet samples were collected by hand from the middle of the flowing portion of the channels. Surface water samples generally had to be collected using a syringe due to the shallow surface layer. Samples were gathered in a syringe that had been rinsed with the sample water then immediately transferred to clean Nalgene bottles. Porewater samples were collected by inserting into the marsh soil a thin plastic tube to the desired depth. Samples were extracted with a syringe and transferred to Nalgene bottles. Samples were filtered in the lab through dedicated Whatman 0.2 micron PES filters and were analyzed by the LSU Department of Agronomy using a Perkin-Elmer Optima 3000 inductively coupled plasma - atomic emission spectrophotometer (ICP - AES). Samples were analyzed for a variety of dissolved constituents including Al, As, B, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Si, and Zn.

Rivulet Source Model

Discharge through the rivulet during dry weather consists of water from two sources, water that recently flooded the marsh and remains chemically similar to water in the bayou (surface water), and water that has been resident in the marsh subsurface long enough to have developed a distinctive chemical makeup (porewater). Based on this assumption, a two source mixing model was utilized to assess the contributions of porewater and surface water to rivulet discharge. The rivulet source model is based on two mass balance equations:

$$Q_r{*}[\ ]_r = Q_p{*}[\ ]_p + Q_s{*}[\ ]_s \qquad (2)$$

and

$$Q_r = Q_p + Q_s \qquad (3)$$

where:

Q_r,Q_p,Q_s = discharge in rivulet (total), of porewater, and of surface water

[ ]r,[ ]p,[ ]s are concentrations of a given constituent in the rivulet, porewater, and surface water. Simultaneous solution of these equations results in an expression for Q_p:

$$Q_p = \{((Q_r*[\ ]r)/[\ ]p)-((Q_r*[\ ]b)/[\ ]p)\} / (1-([\ ]b/[\ ]p)) \qquad (4)$$

The average concentration for all samples during a trip of a constituent in the bayou ([ ]s) and in porewater ([ ]p) are constants in the model, while rivulet discharge (Q_r) and rivulet concentration of a constituent ([ ]r) are known values which vary with time. This leaves Q_p as the sole unknown variable in equation 4. Chemical constituents chosen for use in the mixing model include Mn, P, S, and Si.

Porewater Source Model

The concentration of P in the porewater samples obtained on October 18, 1996 were observed to fall into two groups. Shallow samples obtained between 5 and 25 cm depth (n = 5, avg. depth = 15 cm) were found to range between 0.317 and 1.02 mg l^{-1}, with an average of 0.751 mg l^{-1}. Deep samples (n = 3) obtained at a depth of 85 cm averaged 3.13 mg l^{-1} P ranging between 2.97 and 3.62 mg l^{-1}. This variation with depth permitted the separation of porewater from shallow and deep depth in rivulet outflow. The same two-source mixing model approach used in the rivulet source model was applied to the porewater outflow identified by the first model. The mass balance equations used to develop the porewater source model are:

$$Q_p*[P]p = Q_s*[P]s + Q_d*[P]d \qquad (5)$$

and

$$Q_p = Q_s + Q_d \qquad (6)$$

where:

Q_p = volumetric flow of porewater (l/s)

Q_s = volumetric flow of shallow porewater (l/s)

Q_d = volumetric flow of deep porewater (l/s)

[P]p,[P]s,[P]d = concentration of P in porewater, shallow porewater, and deep porewater.

The simultaneous solution of these equations yields:

$$Q_s = \{((Q_p*[P]p)/[P]s)-((Q_p*[P]d)/[P]s)\}/(1-([P]d/[P]s)) \qquad (7)$$

Q_p is taken as the porewater discharge obtained from the above model using Mn, S, and Si as tracers. The concentration of P in porewater ([P]p) was calculated based on the observation that P concentration in surface water is smaller than the concentration in the porewater by an order of magnitude ([P]s = 0.751, [P]d = 3.13, [P]bayou = 0.052 mg l^{-1}). This permitted the input of P from surface waters to be neglected and all of the discharge of P in the rivulet is attributed to porewater flow. This yields:

$$Q_p*[P]p = Q_r*[P]r \qquad (8)$$

then

$$[P]p = (Q_r*[P]r) / Q_p \qquad (9)$$

where variables are defined as above.

Subsurface Flow Model

The water levels obtained from the three water level gages near the rivulet (Fig. 14) and the measurements of hydraulic conductivity of the soil permit the calculation of subsurface porewater flow into the rivulet. Todd (1967) developed an equation to describe one-directional flow in an unconfined aquifer based on Darcy's law and Dupuit assumptions (velocity is proportional to the tangent of the hydraulic gradient and flow is horizontal and uniform in a vertical section):

$$q = K/2x * ((h_o + dh)^2 - h_o^2) \qquad (10)$$

Where:

q = discharge per unit length of rivulet ($cm^2\ sec^{-1}$)

K = hydraulic conductivity ($cm\ sec^{-1}$)

x = horizontal distance between rivulet and well (cm)

h_o = thickness of subsurface flow at the rivulet edge

dh = the change in water table height between rivulet and well

This equation yields the inflow to a single side of the unit length of the rivulet. The thickness of flow is taken to be the vertical distance between the marsh soil surface and the bottom of the rivulet channel. This distance (approximately 45 cm) is similar to the depth below the marsh surface of a layer of lower permeability soil that is generally encountered in porewater sampling. This layer of low permeability approximates the effects of a non-permeable layer which is assumed in the development of the equation by Todd (1967).

The upper portions of the drainage system behave similarly to lower section, but water level fluctuations and subsurface pressure gradients are less pronounced (Fig. 15). Therefore, the watershed was divided into two sections. The lower section includes 103 m of rivulet and is characterized by conditions at the lower wells, and the upper section includes 200 m of smaller rivulets whose behavior is represented by fluctuations at the upper set of wells. Flow from the upper portion of the watershed was modeled using data from the upper set of wells. However, the upper set of wells was not recording during the periods when discharges were measured in the rivulet. The head difference between the rivulet and well in the upper station averaged 29% of the difference at the lower station. Discharge from the upper portion of the watershed was represented by:

$$q = K/2x * ((h_o + (dh*.29))^2 - h_o^2) \qquad (11)$$

where all variables are as defined above. The total contribution of subsurface flow to the rivulet was calculated by multiplying unit discharge in the lower section by 103 m of rivulet, multiplying the upper section unit discharge by 200 m of rivulet, and summing the two results. Unit discharge for each m of rivulet was multiplied by two to account for flow through both banks of the rivulet. No attempt was made to route the discharge from the upper section to the lower section; discharge at the upper section was assumed to instantaneously arrive at the gaging station. The most remote section of the watershed is less than 150 m of rivulet from the gaging station. At a flow velocity of 0.1 m sec^{-1}, which is a typical value at the gaging station at lowest flows, the travel time from the most remote section of the watershed would be less

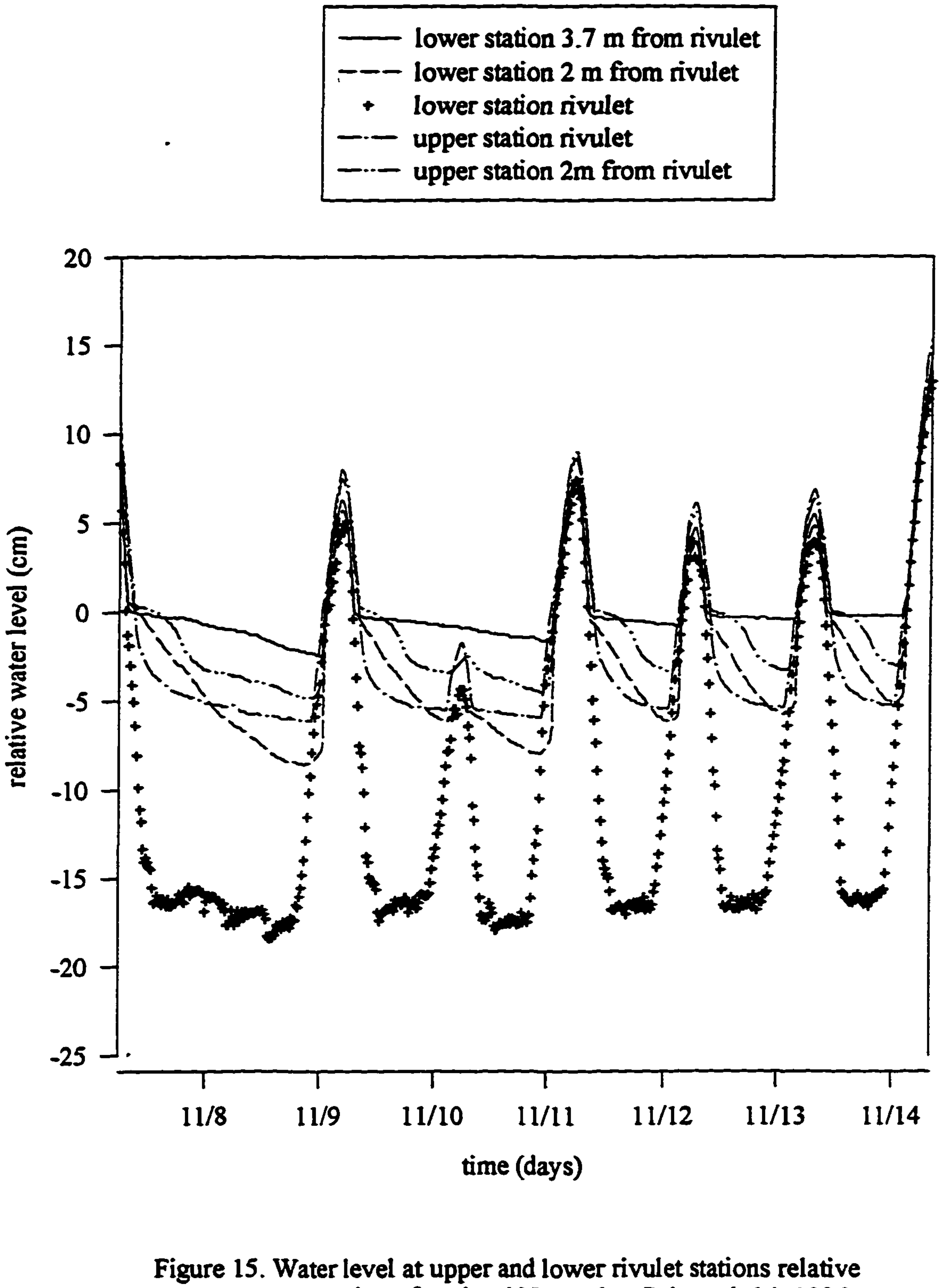


Figure 15. Water level at upper and lower rivulet stations relative to marsh surface level November 7 through 14, 1996.

than 1,500 sec (35 min). This should not have a large impact on results of the model due to the slow changes in subsurface gradients and resulting slow changes in subsurface discharge.

RESULTS

Hydraulic Conductivity

Each of two holes constructed for the auger-hole test for K was drawn down twice, and the position of the water level in the hole recorded every 20 seconds for 6 to 7 min. This allows for numerous calculations of K using various times and water levels. K was calculated numerous times for each drawdown of each hole using equation 1, and results for each individual calculation were generally within 10% of the mean value. The variations between individual calculations was due to the rough measurement of water level, rounded to the nearest cm. Average K for the first hole was 70 m day^{-1} (0.081 cm sec^{-1}), and for the second hole was 62 m day^{-1} (0.072 cm sec^{-1}).

The calibration of the subsurface flow model provided a second estimate of hydraulic conductivity. The model yielded an effective K of 0.004 cm sec^{-1}.

Water Table Fluctuations

Water levels in the three wells near the rivulet and water level in the bayou are shown in Fig. 14. Water levels at the wells in the upper watershed are depicted in Fig. 15. Water levels at all gages respond quickly to changes in water level in the bayou. Water level at the three lower station gages diverges quickly when rivulet water level falls below the marsh surface. A pronounced gradient develops toward the rivulet in the narrow zone where all gages are located. Water level in the well, which is 3.7 m from the rivulet at the lower station fluctuates much less than the water level in the rivulet or in the other well which is 2 m from the bayou, which suggests that the point 3.7 m from the rivulet is located at the outer edge of the zone of influence of the rivulet.

Water table fluctuations at the upper station follow a similar pattern to those at the lower station. The gage in the rivulet at the upper station does not display the rapid fluctuations during low tide that are evident at the rivulet gage at the lower station, due to the lack of a free water surface at the upper station during typical low tides. Flowing water generally remains at the lower station during all low tides, and its level fluctuates unpredictably over a small range, apparently due to winds.

Rivulet Discharge

Rivulet discharge is shown in Fig. 16, 17 and 18. Of the three sampling periods reported here, only on October 18, 1996 did the tide rise above and fall below marsh surface level to produce a complete, undisturbed runoff hydrograph. On November 26, 1996, high tide flooded the rivulet channel but did not flood the marsh surface due to the passage of a cold front the previous day. Strong northerly winds following the cold front passage resulted in lowered water levels and muted tidal fluctuations in Barataria Bay. Similar phenomena occurred during several other sampling days for which data are not shown here. Our experiences with tides that either failed to rise or fall as predicted underscores the unpredictability of Barataria Bay tides and the episodic nature of porewater discharges. During the runoff period

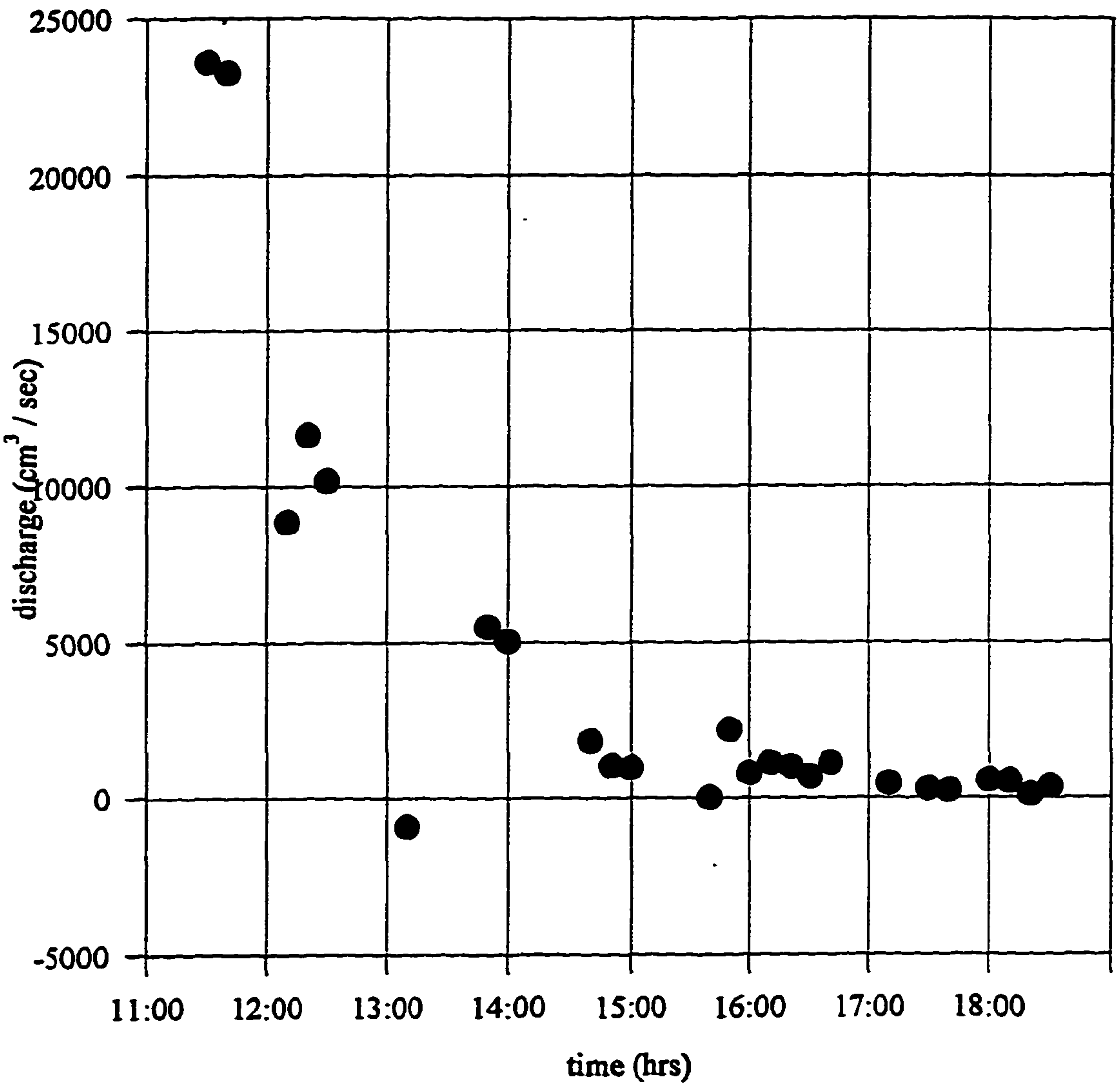


Figure 16. Measured discharge in rivulet 18 October 1996.

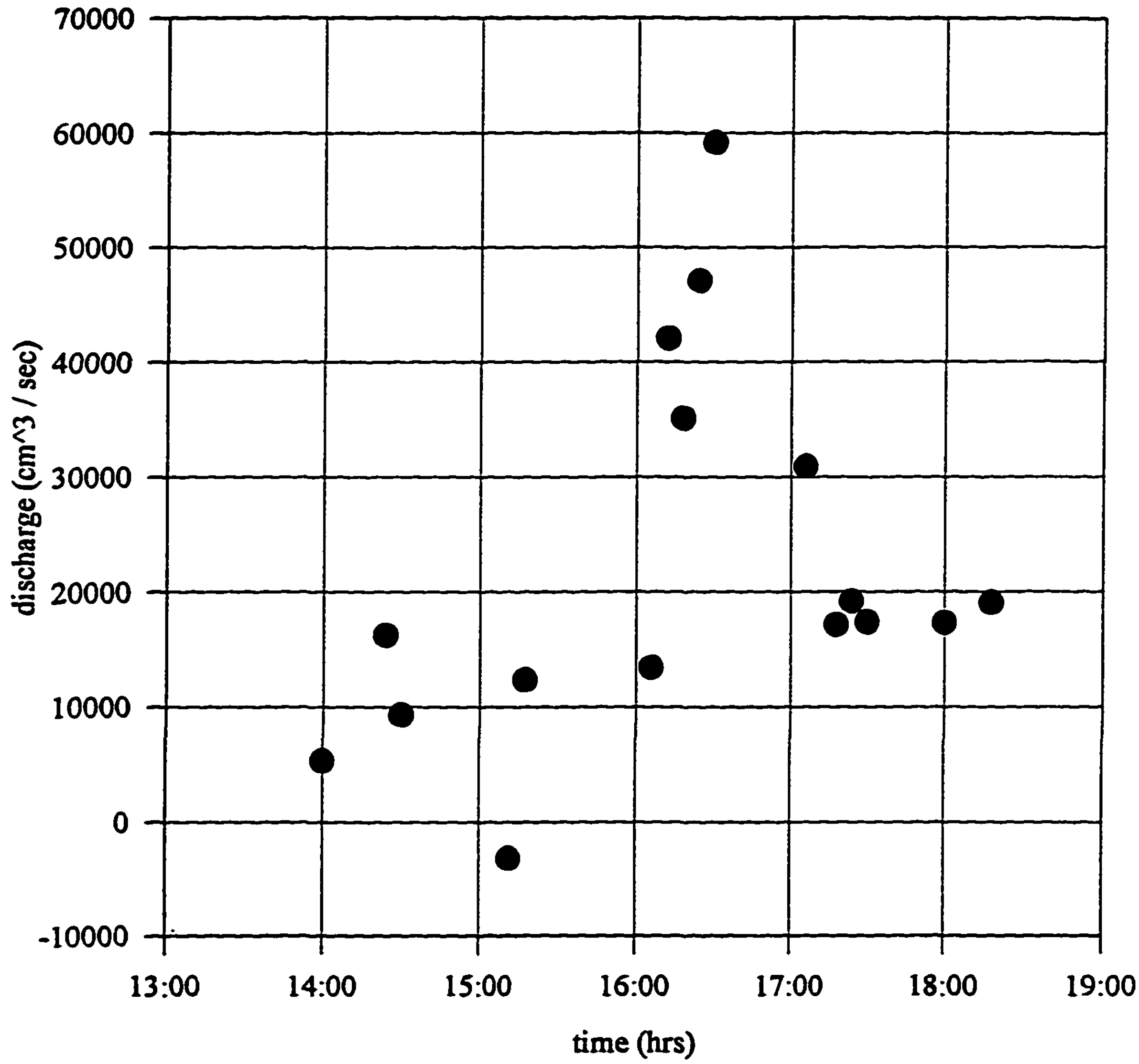


Figure 17. Measured discharge in rivulet on 20 September 1996.

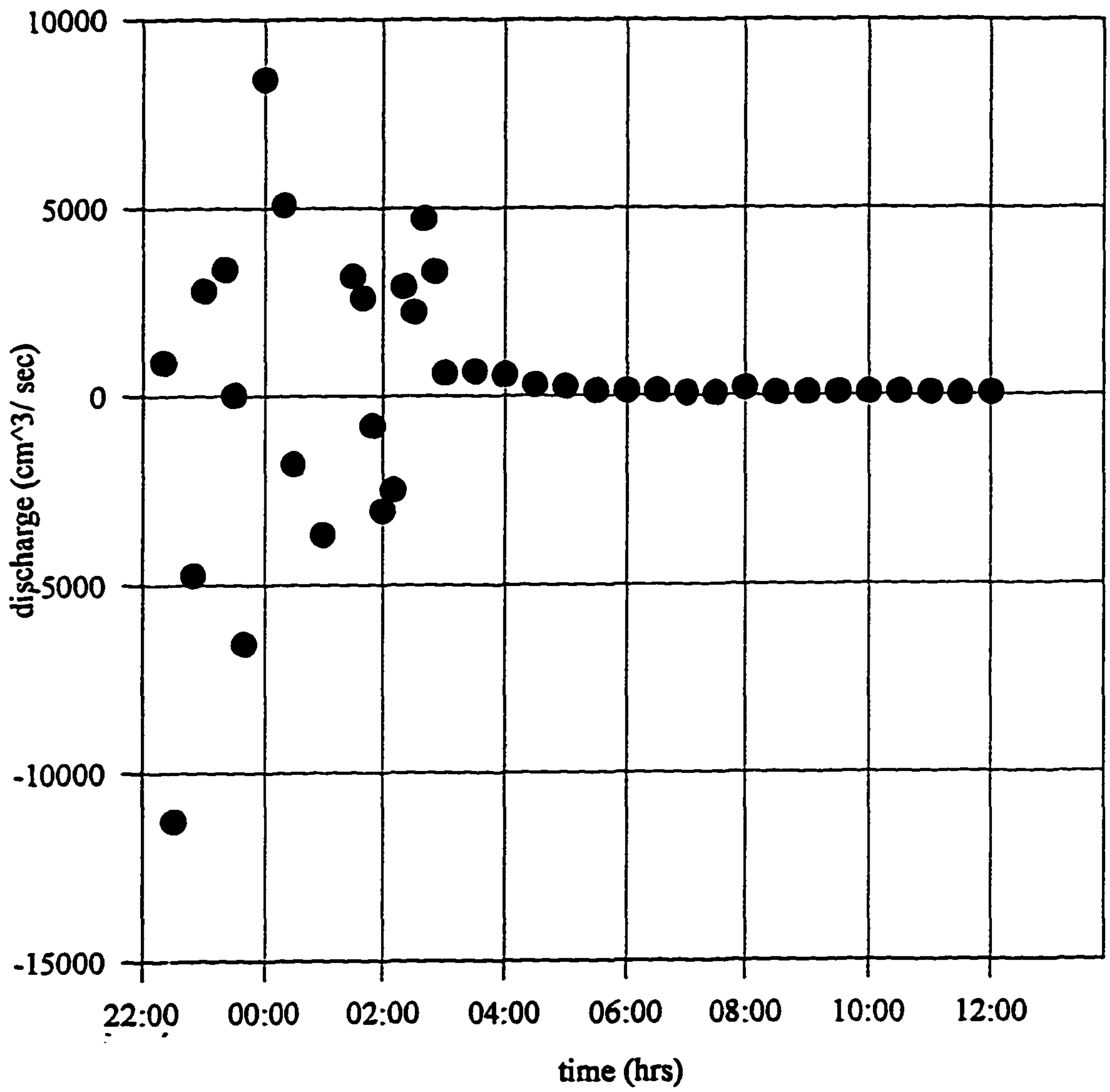


Figure 18. Measured discharge in rivulet on 26 November 1996.

of September 20, 1996, several intense thunderstorms brought heavy rains to the study site. The large influence of these rains on discharge volume is evident in Fig. 18, the large increase in discharge volume coincides with changes in discharge chemistry that result from dilution of runoff water by rainwater. Although the rainfall yielded interesting insight into sediment erosion from the marsh surface, reported in Chapter 3, the dilution of marsh surface chemistry and disturbance of the rivulet discharge hydrograph renders the September 20 data difficult to interpret in terms of porewater discharge, and as a result the day's data will not be emphasized here.

Water Chemistry

Measured concentrations of several constituents are shown in Fig. 19, 20, 21, and 22. Many other constituents were examined; of the numerous constituents examined, Mn, P, S, and Si appeared on initial examination to occur in high enough concentrations, and to occur in sufficiently dissimilar concentrations in the porewater and surface water to be useful as tracers of porewater export through the rivulet. Concentrations of all chemical constituents in the bayou are typically uniform throughout the sampling periods, and are assumed to represent the concentrations in bayou water that flooded the marsh at high tide. Porewater concentrations often vary spatially, but do not vary with time, and for this reason average porewater concentration of a chemical is taken to represent average conditions at all times during the sampling period. Marsh surface constituent concentrations generally show spatial variability as well as considerable temporal variability. The spatial variability, particularly evident during later stages of runoff, can be attributed to uneven

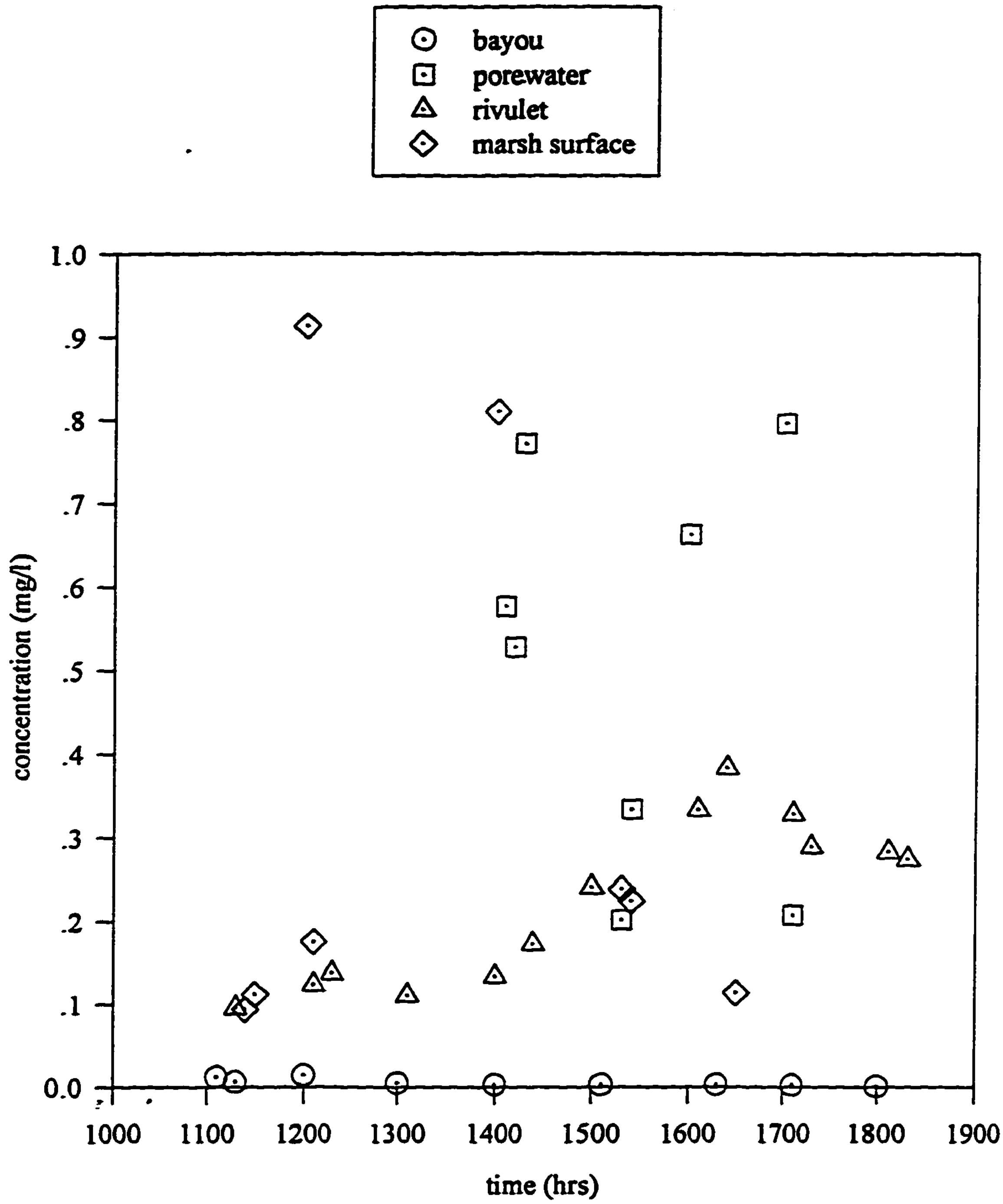


Figure 19. Mn concentrations on 18 October 1996.

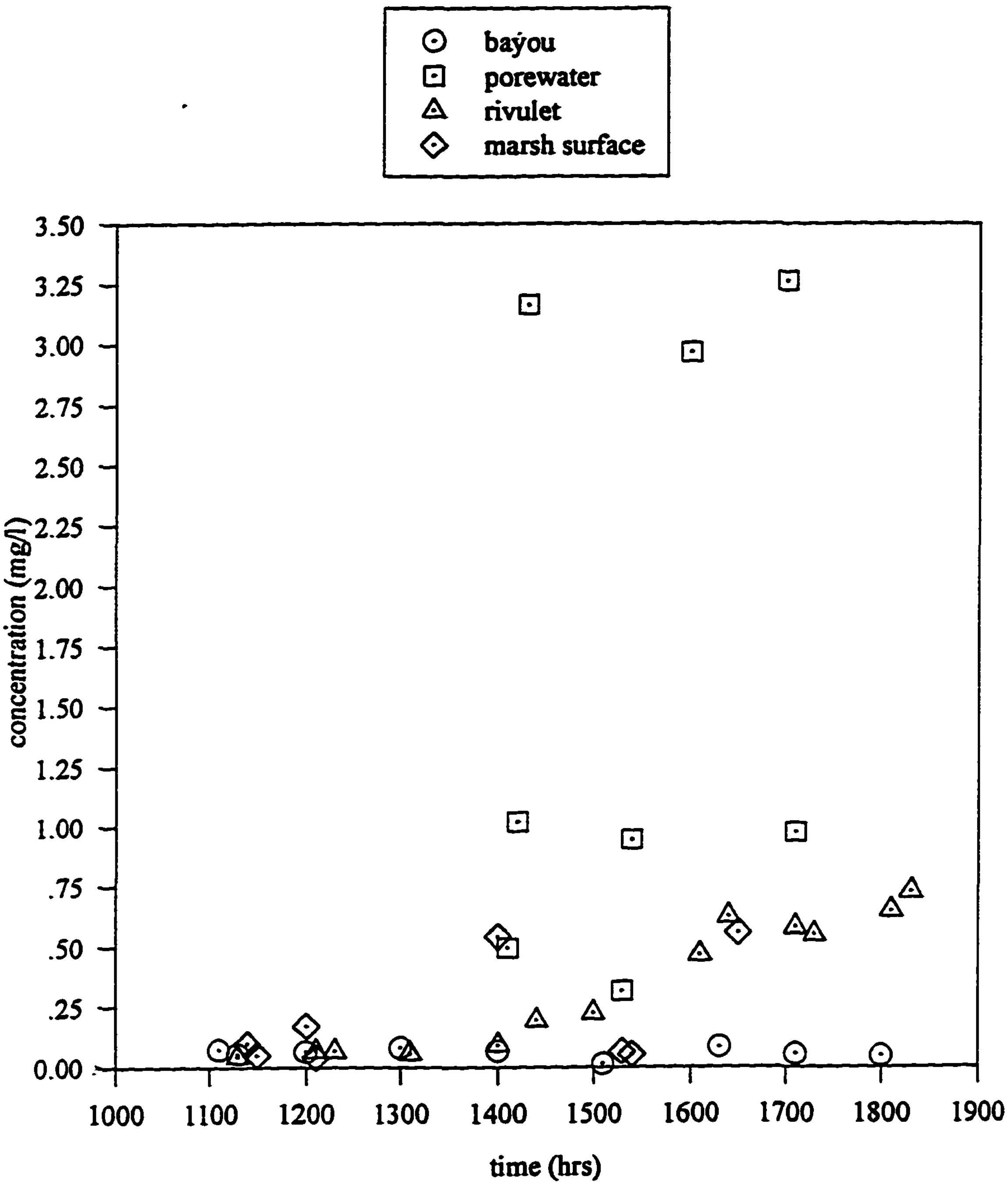


Figure 20. P concentrations on 18 October 1996.

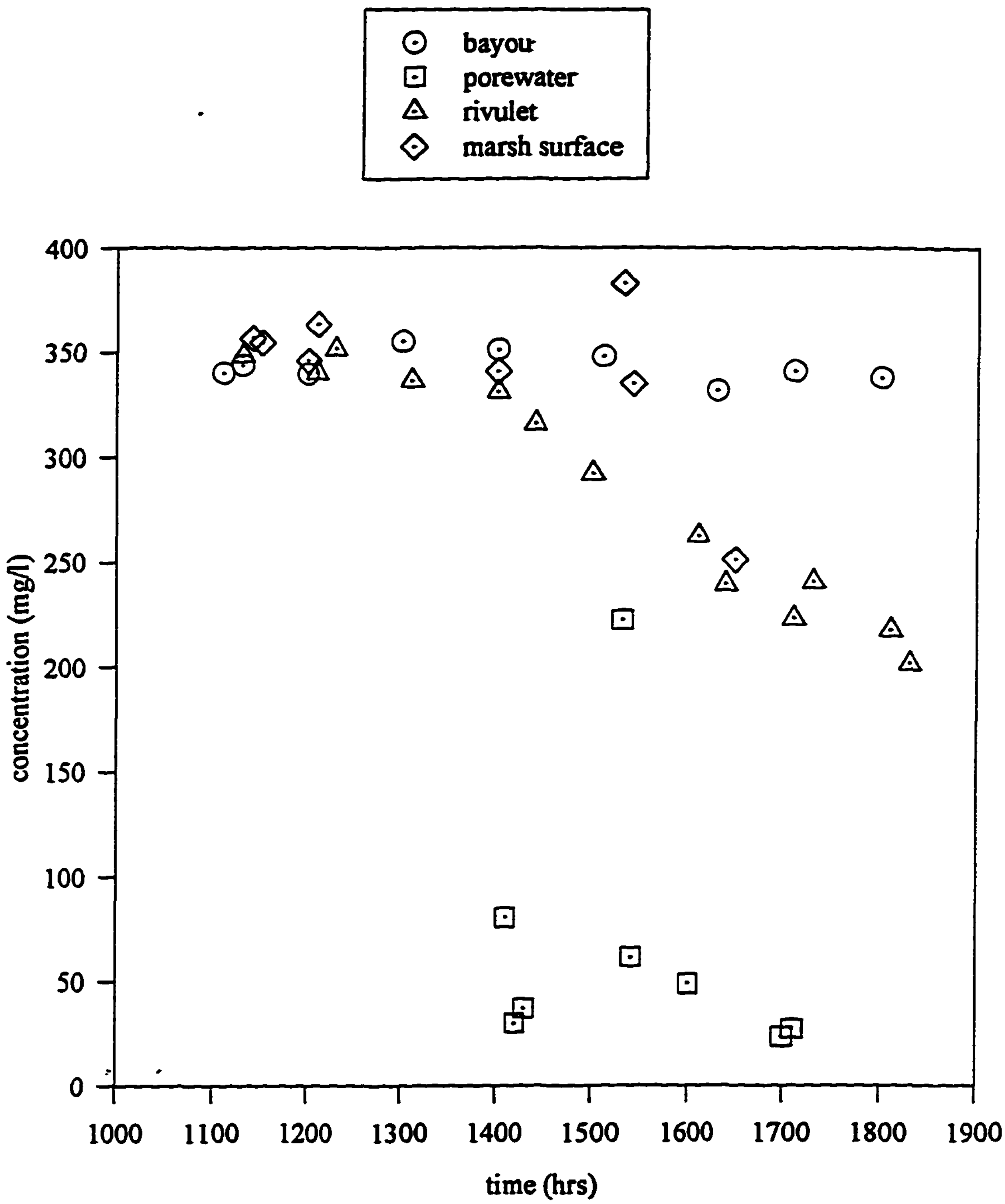


Figure 21. S concentrations on 18 October 1996.

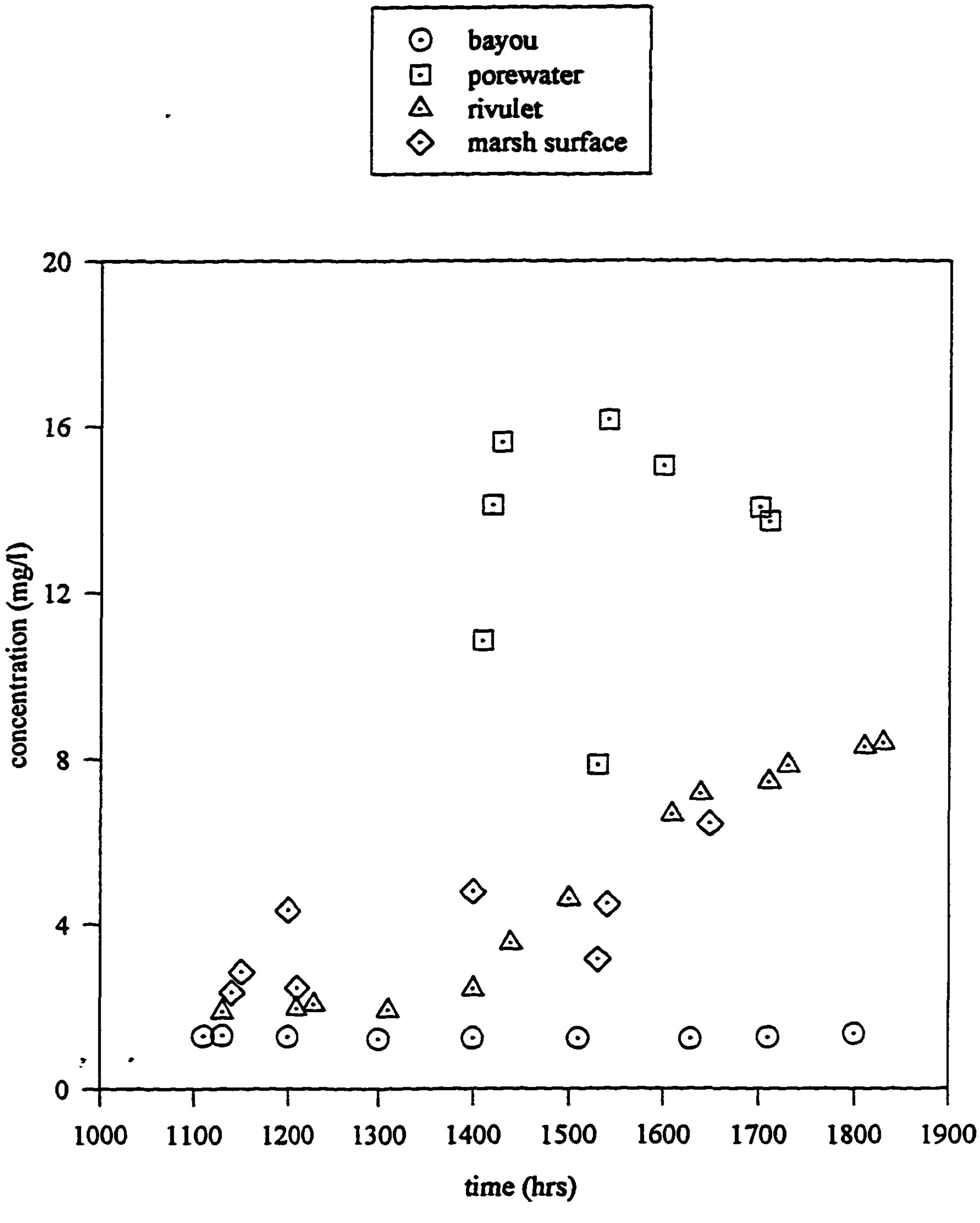


Figure 22. Si concentrations on 18 October 1996.

distribution of surface water and variable depth at that time as well as to difficulty in sampling the very thin surface water layer after a few hours of marsh surface exposure; spartial variability is due to the diffusion of porewater constituents into the surface water as water stands on the marsh surface.

Rivulet Source Model

Of the chemical constituents examined, Mn, P, S, and Si were selected for use in the rivulet source model (equation 4). The results of the model runs with these constituents are shown in Fig. 23. The results of model runs using Mn, S, and Si are similar and were averaged to produce an estimate of porewater discharge. Result obtained by using P in the rivulet source model differed from results of other constituents for reasons that are discussed below. Rivulet source model results indicate that the discharge of chemical constituents typical of porewaters is relatively constant during the rivulet discharge period.

Porewater Source Model

The porewater source model (equation 9) was applied only to P data, and results are shown in Fig. 24. Model output indicates that contributions of porewater from deep in the marsh subsurface occurs only during later stages of rivulet discharge.

Subsurface Flow Model

The physical model of subsurface flow (equation 10) was calibrated to rivulet hydrograph recession flows based on the output of the rivulet mixing model and water chemistry sampling. During model calibration physical variables that could be

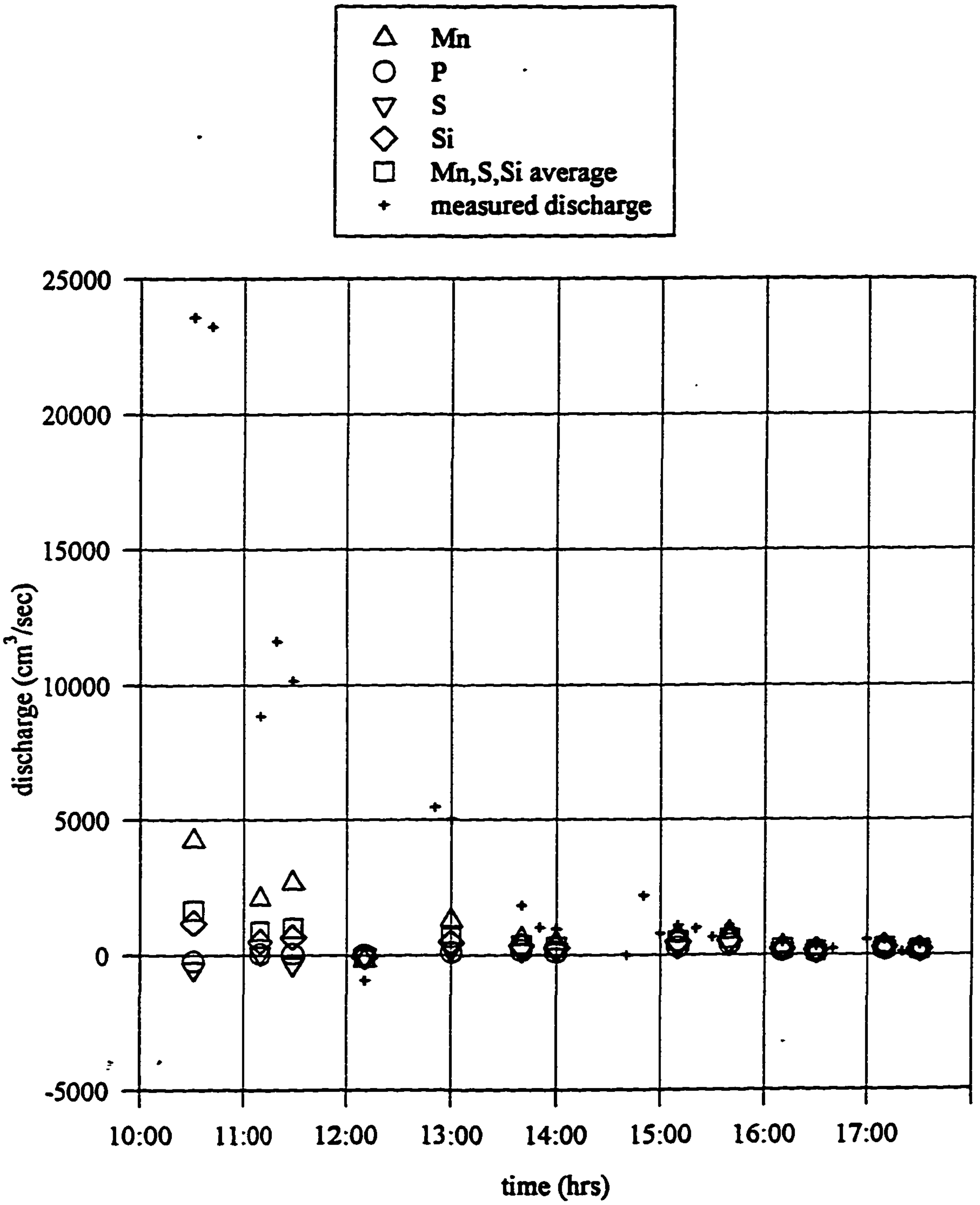


Figure 23. Rivulet source model results for 18 October 1996.

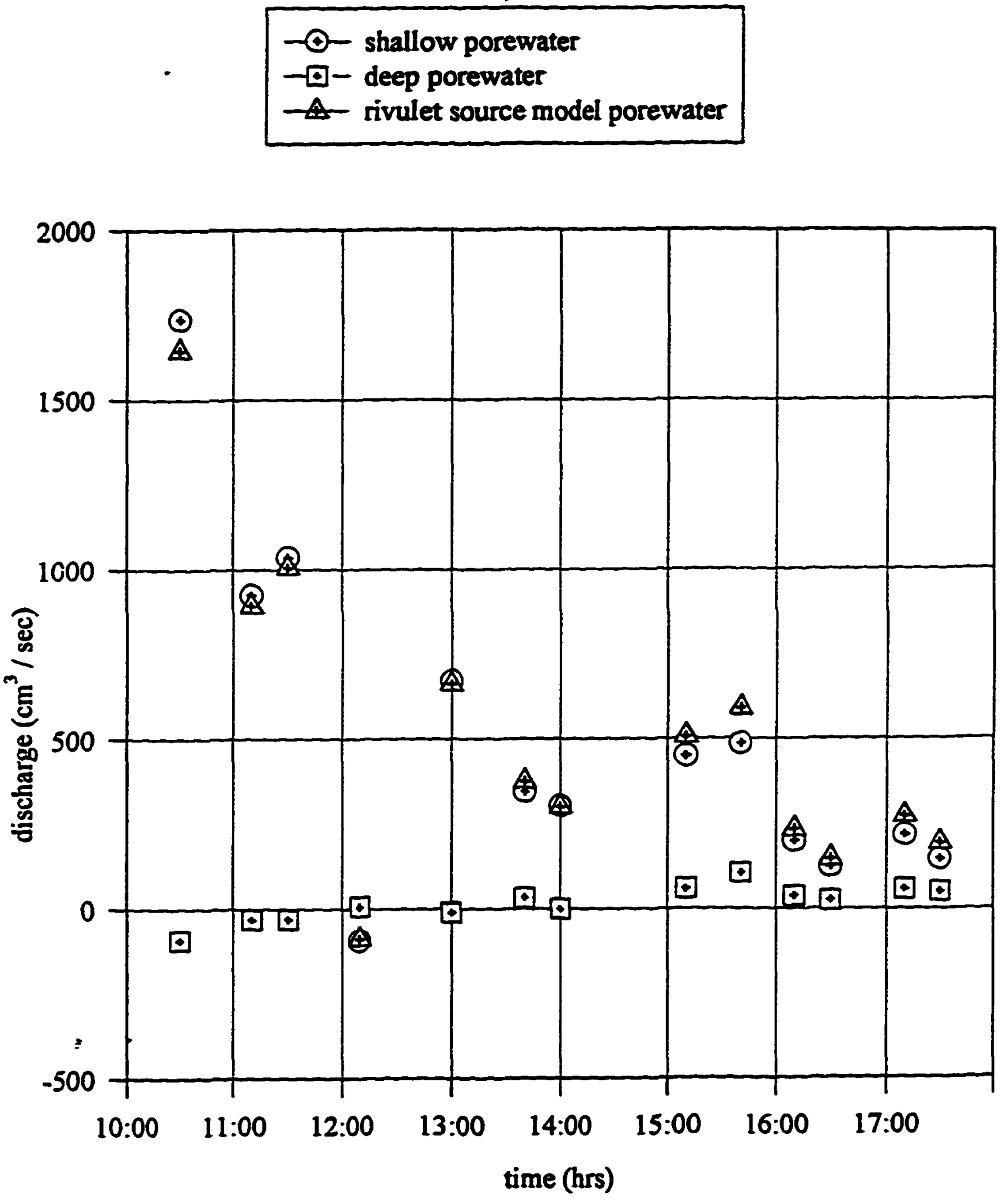


Figure 24. Porewater source model results for 18 October 1996.

measured with some dependability, including total length of the rivulet, depth to low-permeability layer, depth to the bottom of the rivulet channel, and horizontal distance between the rivulet and wells were kept constant, leaving hydraulic conductivity as the only variable to be adjusted to fit model output to observed discharge values. Model output (Fig. 25) was adjusted to roughly fit measured discharge during the recession portion of the hydrograph. The relatively small amount of data available for calibration were considered insufficient to warrant a more rigorous calibration procedure. Thus, model calibration serves as an independent estimate of effective soil hydraulic conductivity which yielded an estimated K of 0.004 cm sec^{-1}. This value is an order of magnitude less than K estimated by the Auger Hole method, and falls within the range of K values reported for peats (Freeze and Cherry 1979). The subsurface flow model, as calibrated using data from October 18, 1996, was applied to data from November 27, 1996. Results are shown in Fig. 26.

DISCUSSION

Hydraulic Conductivity

The hydraulic conductivity measured here, which averaged 66 m day^{-1}, or 7.6 * 10^{-2} cm sec^{-1}, is among the highest reported values for salt marshes, and is in the range of values reported for sands (Mitsch and Gosselink 1993). The organic soils at the study site are similar to peats, for which a very wide range of K, from 10^{-8} to 10^{-2} cm sec^{-1}, have been reported (Mitsch and Gosselink 1993). Values reported for salt marsh soils range from 7.4 x 10^{-4}cm s^{-1} (Harvey et al. 1987) to 26 cm d^{-1} (3 x 10^{-4} cm sec^{-1}) (Yelverton and Hackney 1986), up to 2600 cm s^{-1} in the high

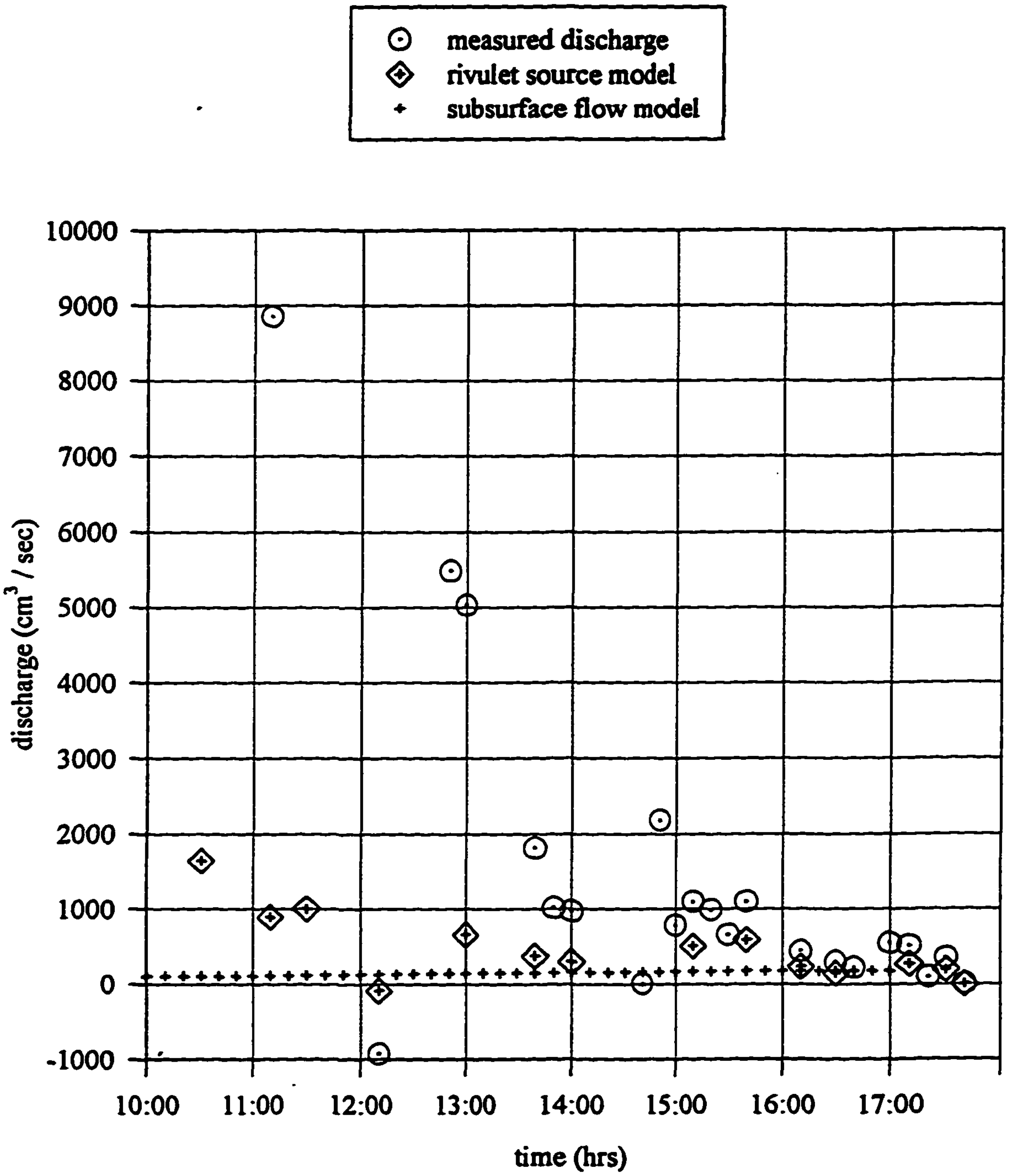


Figure 25. Subsurface flow model and other estimates of subsurface discharge for 18 October 1996.

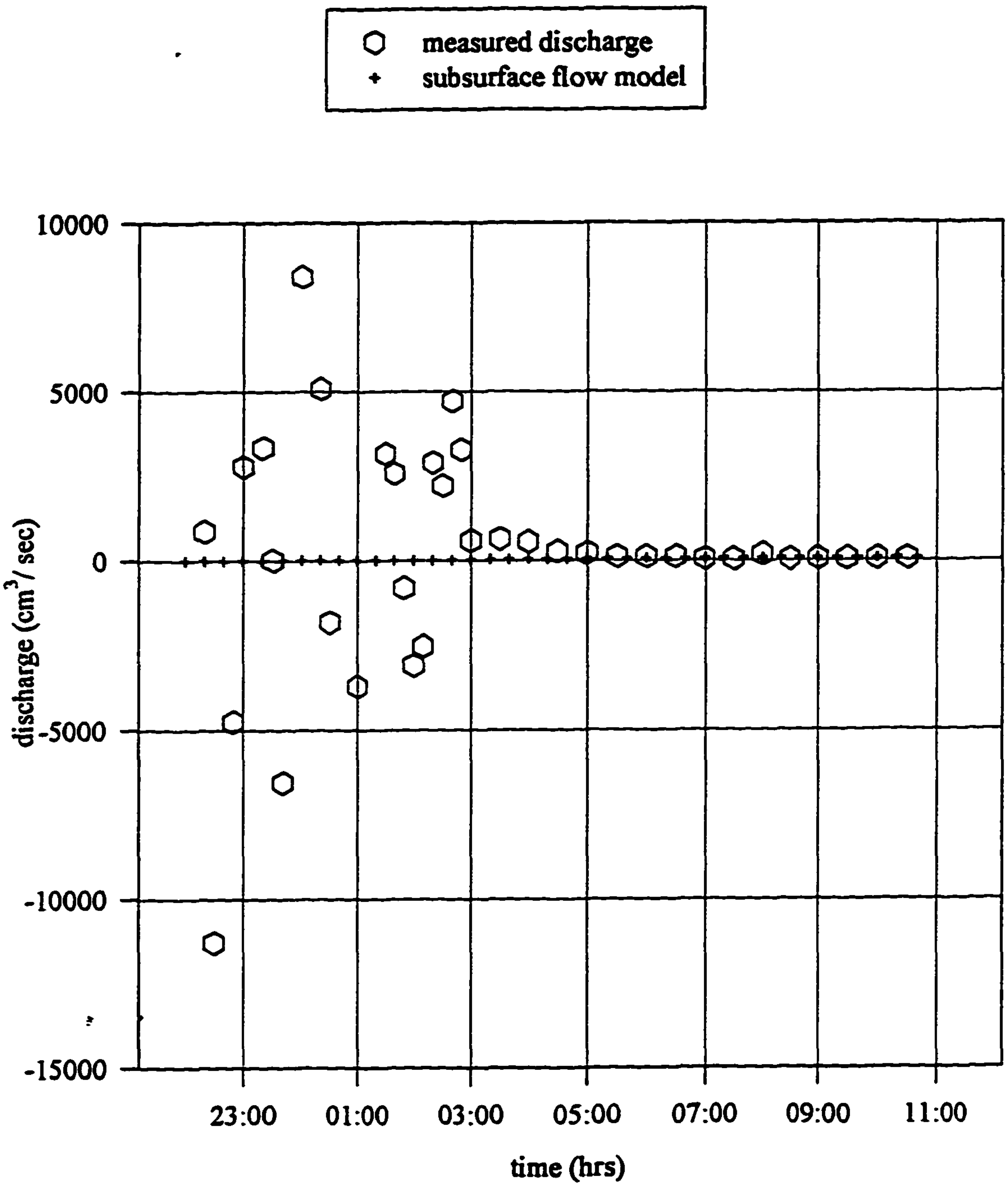


Figure 26. Subsurface flow model results for 27 November, 1996.

permeability zone of a New England salt marsh (Hemond and Fifield 1982). This third value is of the same magnitude as the value reported here, and was measured in a peat below the rooting zone of marsh vegetation, which suggests that the high hydraulic conductivity reported here may be the result of highly organic soils below the rooting zone of marsh vegetation dominating inflow into the boreholes.

Calibration of the subsurface flow model yielded a roughly estimated K of 0.004 cm sec^{-1}, an order of magnitude less than that estimated by the Auger Hole method. Hemond and Fifield (1982) found that a zone of very high K (2,600 cm sec^{-1}) exists beneath the rooting zone of vegetation in a New England salt marsh peat, but that hydraulic conductivity of the rooting zone is 3 orders of magnitude lower. The much lower estimate of K obtained from rivulet discharge suggests that rivulet discharge may be much more strongly influenced by a lower permeability surficial layer than is recharge of an auger hole. The discovery that a majority of subsurface flow appear to originate in shallow soils (see below) supports this idea.

Water Table Fluctuations

Water levels in the marsh soils, rivulet and bayou (Fig. 14) demonstrate that a pressure gradient develops in the marsh subsurface when water level in the bayou and rivulet fall below the level of the marsh surface. This gradient results in porewater flow toward the rivulet and porewater discharge from the marsh. The gradient disappears when water floods the marsh surface, indicating that subsurface flow occurs only while the marsh surface is exposed. Figure 15 demonstrates that in upper portions of the watershed, water table fluctuations near the rivulet are similar to those in the lower portions. The main difference in the behavior of the upper and lower rivulets is that the upper portions respond to bayou water level changes with smaller magnitude fluctuations, and water tables in upper portions of the watershed stay closer to the marsh surface than do water tables in lower portions of the watershed. Water level in the upper rivulet does not drop as far as water level in the lower rivulet due to the shallower rivulet at the upper station. The rivulet bottom acts as a lower boundary for water table drop at both stations, but the rivulet bottom is closer to the marsh surface at the upper station than at the lower station, resulting in less extreme water table fluctuations.

The function of the rivulet bottom as a lower limit for water table fluctuations suggests that the depth of the rivulets plays a role in regulating plant growth and porewater chemistry in the marsh. Porewater chemistry in salt marshes is strongly influenced by anaerobic conditions resulting from persistent soil saturation (Mitsch and Gosselink 1993), which in turn affects plant growth and productivity. Persistent waterlogging of wetland soils and increased anaerobiosis has been implicated in the deterioration of Louisiana coastal marshes (Salinas et al. 1986; Delaune et al. 1989). The presence of a rivulet drainage network on the marsh surface provides drainage for interior marsh areas, and in doing so may reduce anaerobiosis in certain parts of the marsh and contribute to overall productivity and marsh health.

The most inland well at the lower rivulet station (Fig. 14) is located 3.7 m from the rivulet, and water level at the well fluctuates much less than does water level in the rivulet. This suggests that the well is located at the edge of the zone where active water level fluctuations and horizontal porewater flow occurs; this zone is thus approximately 7.5 m wide, centered on the rivulet. Figure 15 demonstrates that in the upper watershed, water table response appears to be similar to what occurs at the lower station. The two wells (Fig. 15) that are located 2 m from the rivulet at the lower and upper stations respond similarly to water level drops in the rivulet. Thus it appears that water table drawdown occurs along the entire length of the rivulet, although the magnitude of changes is less in upper portions of the watershed. A narrow zone of active porewater flow bordering tidal creeks has been identified by numerous researchers (Hemond and Fifield 1982; Agosta 1985; Hackney 1986; Yelverton and Harvey et al. 1987; Nuttle 1988). These earlier researchers identified the zone along tidal creeks that are much larger and deeper than the rivulet examined here. The presence of such zones along small rivulets indicates that much more of the marsh area is involved in porewater export and subject to water table fluctuations than would be if water table fluctuations occurred only along major tidal channels. There are approximately 297 m of rivulet connected to the rivulet system studied here. An active zone 7.5 m wide stretching along 297 m of rivulet results in 2228 m^2 of marsh surface area experiencing active porewater flow and water level fluctuations. The drainage area of the rivulets is approximately 10,000 m^2, thus 2228 m^2 represents 22% of the surface area of the marsh.

The horizontal flow of porewater near creek banks plays an important role in supporting the growth of plants living on the creekbank. Water exported from the creek banks zone is replaced by nutrient-rich water from interior marsh areas providing nutrients to creek bank plants, and the lowering of water tables in creek banks results in more oxidized sediments and better drainage in these areas than in interior areas of the marsh (Agosta 1985). Therefore active porewater flow and water table fluctuations in areas of the marsh that are not adjacent to major tidal creeks has important implications for nutrient cycling and productivity of the marsh.

Naturally Occurring Hydrologic Tracers

Concentrations of a variety of chemical constituents of water in the bayou, porewater, rivulet discharge, and in marsh surface water remaining after marsh exposure by the falling tide were examined. An initial examination of the results of chemical analyses indicated that many of the elements for which samples were analyzed showed little promise as tracers of water sources. In order to be a useful tracer an element must occur in different concentration in porewater than in bayou water, and its concentration should be relatively consistent in each of the two waters. Addition desirable characteristics include low chemical reactivity which ensures that a tracer will be relatively conservative, and a large difference in concentration between the two water sources. Of the several elements which were initially examined, Mn, P, S, Si showed the most promise as tracers and were used for additional study.

Samples of water on the marsh surface were collected from various parts of the watershed during runoff measurement periods. Soon after the marsh is exposed the surface layer of water is relatively deep and continuous on the marsh surface. This permits easy collection of samples with minimal soil disturbance and ensures that chemical characteristics of the water are fairly uniform everywhere on the marsh. The uniformity of chemical composition of surface water early in runoff and the similarity of the surface water to bayou water is evident in Figs. 19 through 22. As the marsh remains exposed and the surface water thins, sampling becomes more difficult and prone to disturbance of the soil, and marsh surface samples frequently must be collected from depressions and small channels on the marsh surface. These later samples are less uniform than earlier samples, and certain sampling locations, such as small channels, could more properly be considered part of the rivulet system than part of the marsh surface layer.

Of the four elements chosen as tracers, only Silica (Si) can be considered fairly unreactive and thus a conservative tracer. Since the rivulet source model applied here is based on an assumed balance of dissolved constituents, the use of conservative tracers is important to the success of the model. Sulfur (S) occurs in several different states in salt marshes depending on reduction/oxidation conditions, and certain forms are highly reactive. The abundant soluble sulfur in seawater can be combined with iron to form insoluble pyrite in reduced marsh soil, or soluble reduced sulfur compounds leaving reduced soil environments may be oxidized by sulfur bacteria on the marsh surface to elemental sulfur (Mitsch and Gosselink 1993). Deposits of elemental sulfur are frequently visible in rivulets at the study site indicating that soluble sulfur is removed from solution and thus may not be a conservative tracer. Phosphorous (P) is an important nutrient for the growth of plants and bacteria, and is therefore subject to uptake. Manganese (Mn) is a micronutrient that may potentially be absorbed by plants or bacteria to support their growth, but is generally not in short supply nor high demand in the salt marsh (Mitsch and Gosselink 1993).

Despite their potential for non-conservative behavior, S and Mn produced similar results to Si in the rivulet source model (Fig. 23). Although at a given point in time the three tracers yield three different estimates of porewater discharge, the generally good agreement of the three tracers indicates that all are conservative enough to be useful. The results obtained using P differ significantly from the other three results, apparently due largely to the variation of P concentration with depth rather than non-conservative behavior of dissolved P. The average P concentration of all porewater samples is increased by the high concentration in several samples from relatively deep (85cm) in the marsh soil. As discussed below, the majority of porewater flow originates in shallow soils, thus the use of average P concentration skewed by high concentrations at depth leads to an artificially low estimate of porewater discharge, which can be seen in Fig. 23.

Rivulet Discharge

Water that is discharged from the watershed via the rivulet can have three possible sources at this study site. Water floods the marsh from the bayou during high tides, and much of this water leaves the marsh while still retaining the chemical characteristics of bayou water (surface water). Other water, although it may have originated in the bayou, has been resident in the marsh soil long enough to acquire distinctive chemical characteristics (porewater). The third source of water is rainfall, which also has a distinctive chemical makeup characterized by low concentrations of all of the characteristic chemicals of bayou and porewater for which water samples were analyzed here. Rainfall is, of course, a potential source of water only on certain days.

Two different mechanisms of water runoff from the marsh have been theorized to occur in tidal marshes exposed by low tides: movement of water through subsurface soil and subsequent seepage into channels; and movement of water as a thin surface layer (Gardner 1975). The thin surface layer of water on tidal marshes becomes enriched in porewater constituents by diffusion and by exchange of water between the surface layer and near-surface soils. Thus a complete understanding of the hydrologic processes that result in discharge of water through the rivulet during marsh surface exposure requires that the contributions of the several potential water sources and runoff mechanisms be identified. Several methods of analysis were employed in efforts to distinguish water sources and runoff mechanisms including analysis of constituent concentrations in marsh water, application of a chemical mixing model to identify discharge sources, and examination of subsurface pressure gradients that control subsurface water movement.

The discharge curves measured on October 18, 1996 (Fig. 16) shows an expected pattern of high runoff during initial stages of discharge which quickly drops off to form a recession curve typical of the hydrographs of larger watersheds. In a typical larger watershed, peak flows are attributed to overland flow and subsurface storm flow, while baseflow, represented by the slowly declining lower volume flows later in the hydrograph, are attributed to deeper, and therefore more varying groundwater flow (Freeze and Cherry 1979). Several lines of evidence suggest that a similar situation exists in this small marsh watershed and will be discussed below. The discharge hydrographs recorded at the site on September 20, 1996 (Fig. 17) and November 26-27, 1996 (Fig. 18) illustrate the variability that exists in runoff behavior of the watershed. Discharge on September 20, 1996 (Fig. 17) was initially similar to runoff on October 18, 1996, but a thunderstorm passing over the watershed caused rapid changes in the volume and chemistry of discharge. The hydrograph of November 26, 1996 (Fig. 18) resulted from a high tide which peaked below the level of the marsh surface but which flooded a portion of the rivulet channel. This caused erratic, reversing flows during high slack tide which switched to unidirectional, outgoing flow during the ebb tide. Note that although the marsh surface did not flood during the November 26, 1996 high tide, once the rivulet channel drained a recession curve similar to that of October 18, 1996 was observed. This suggests that bayou water flooding the marsh surface is not the source of runoff during late stages of the discharge hydrograph, but rather water stored on the marsh surface or within marsh soils supplies the rivulet during low flow discharges.

The rivulet source mixing model results (Fig. 23) indicate that porewater constituent contribution to rivulet discharge is relatively constant throughout the runoff period observed on October 18, 1996. In contrast, the pressure gradient that is created in the marsh subsurface along the rivulet during marsh exposure (Fig. 14) increases as time passes. This indicates that subsurface flow of porewater and seepage into the rivulet cannot be the primary mechanism of enrichment of chemicals in the rivulet, particularly during the early portions of runoff, when the pressure gradient is smallest, and suggests instead that overland flow of a surface layer of water predominates. Another piece of evidence that points to surface flow into the rivulet is the similarity between tracer concentrations in the rivulet and in marsh surface waters early in the runoff period. Marsh surface water chemistry and rivulet water chemistry are nearly the same, which suggests that the marsh surface is the primary source of both water and chemicals to the rivulet during this time.

During the later stages of rivulet discharge, several pieces of evidence suggest that subsurface flow plays a larger role in discharge than in earlier stages. The rivulet source model indicates that porewater contributions may account for a large part of rivulet discharge once the slowly declining, more horizontal part of the discharge curve is reached (Fig. 23). Additionally, at this time subsurface pressure gradients are at their largest, indicating that the largest potential for subsurface flow exists. A third indication of the larger role of subsurface flow at this time is the rising concentration of chemicals in the rivulet (Fig. 19 through 22). During the gradually receding stage of rivulet discharge, rivulet concentrations approach porewater concentrations of the illustrated constituents, while marsh surface concentrations show a tendency to rise (or in the case of S concentration, fall) more slowly, suggesting that water remaining on the marsh surface is not the only source of rivulet discharge, but rather it is supplemented by porewater containing higher concentrations of chemicals.

A final indication of the influence of subsurface flow on late stages of rivulet discharge is provided by the porewater source model. Phosphorous concentrations in shallow porewater (5 to 25 cm depth) average 0.751 mg l^{-1}, while the concentration at 85 cm depth averages 3.13 mg l^{-1}. This, as well as the near absence of P in bayou waters, permitted the construction of a model designed to differentiate the contributions of shallow and deep porewaters to rivulet discharge. The porewater source model indicates that deep porewater contributes to rivulet discharge only during later stages of rivulet discharge (Fig. 24). This is not unexpected due to the steeper hydraulic gradient in the soil and lowered water tables late in runoff, and supports the idea that true subsurface flow contributes to the later stages of rivulet discharge.

Subsurface Flow Model

The discharge hydrograph measured on October 18, 1996 (Fig. 16) includes a tail that represents slowly receding discharge suggestive of baseflow observed in the hydrograph of larger watersheds. This is especially evident in the November 26, 1996 hydrograph (Fig. 18) which, despite minimal marsh flooding during the previous tide, includes an extended period of low volume runoff suggestive of baseflow. Observations at the study site of low volume discharge at times when the marsh surface has been exposed for several days also suggest the occurrence of continual runoff. The evidence for subsurface flow contributions during later stages of the discharge hydrograph which are discussed above and the observations of low volume discharge continuing long after marsh exposure provide the basis for calibrating a subsurface flow model of porewater discharge into the rivulet to match rivulet discharge during low volume discharge periods. Model output was adjusted to approximate discharge measured during October 18, 1996 and the resulting value of K, as well as other constants in the model, were used to calculate subsurface flow discharge using water level data from November 26, 1996 (Fig. 26). The approximate fit of the model output to the November 26, 1996 data was accepted as proof that the model has the potential to predict baseflow discharge from the rivulet and that the value of K obtained from the model approximates the effective K of the soils in the watershed.

Annual Porewater Discharge

After matching the subsurface flow model output to the October 18, 1996 discharge data (Fig. 25) and checking results with the November 26, 1996 data (Fig. 26), the model was applied to data for the entire year to produce a rough estimate of porewater discharge from the marsh throughout the year. Subsurface gradients observed at the well in the marsh were used as model input. Table 6 lists subsurface porewater discharge into the rivulet by month during 1996 and 1997. The ten months' estimates that are available total 434 m^3 of porewater, or an annual estimated export of 521 m^3. This amounts to 5.2 cm of water depth for the watershed. Monthly discharges range from 11.4 m^3 during April 1997 to 75.6 m^3 during May 1996. This variation reflects the variation in marsh surface inundation at the site (Table 6). The figures in Table 6 represent minimum estimates of the export of porewater from the marsh, since only baseflow in included in the estimates. The total export of porewater constituents is certainly much larger than would result from the porewater estimate of Table 6 due to considerable porewater constituent export resulting from surface flow runoff into the rivulet during tidal exposure. The enrichment of the surface layer of water with porewater constituents has been attributed to chemical diffusion into the surface layer and bioturbation by marsh surface organisms (Gardner 1975). Diffusion of porewater constituents should occur even more rapidly while marshes are flooded than while they are drained, and potentially could account for much more porewater constituent export than is produced by subsurface discharge.

Biogeochemical Implications of Rivulet Discharge

The discharge of porewater and porewater constituents from the marsh represents a potential source of nutrients and other chemicals to estuarine waters. While this project was not designed to evaluate the inputs of chemical constituents to the estuary and the preliminary results from only one location do not support any conclusions regarding the effects of porewater exports in the estuary, some rough

Table 6. Estimated monthly subsurface porewater discharge through rivulet.

Month	Discharge (m^3)	Month	Discharge (m^3)
May 1996	75.61	November 1996	38.02
June 1996	60.68	December 1996	n/a
July 1996	68.97	January 1997	n/a
August 1996	44.15	February 1997	59.55
September 1996	25.97	March 1997	42.68
October 1996	7.24	April 1997	11.40

estimates of the potential exports of porewater constituents will serve to emphasize the potential importance of this previously unstudied phenomenon in Louisiana's coastal zone.

There are approximately 63,356 ha of salt marsh in the Barataria Basin (Conner and Day 1987). Porewater export measured here amounted to a minimum export of 5.22 cm yr^{-1}, which would mean an input of 33,000,000 m^3 of porewater to the estuary. The dissolved P concentration in the upper 25 cm of marsh soil, where most porewater exports originate, is 0.751 mg l^{-1}, indicating that 25,000 kg yr^{-1} of dissolved P may be exported from Barataria Basin salt marshes. For comparison, Madden and Delaune (1987) estimated that the total loading of P to the upper Barataria Basin from the largely agricultural uplands amounts to 130,000 kg P yr^{-1}, and that runoff from suburban New Orleans, which is blamed for the eutrophic condition of Lake Cataouatche, contains P loading of 0.56 mg l^{-1}. Thus it is evident that the P export from tidal marshes may be a significant import to the Basin. Other constituents are exported to the estuary in proportion to their concentration in porewater. A variety of micronutrients including Mn, Fe, and K, macronutrients like P and ammonium, elements of geochemical importance such as Fe and S, and dissolved carbon are present in porewaters in concentrations above those in surface waters, indicating that their export may enrich estuarine waters.

CONCLUSIONS

The discharge of water through a small marsh surface rivulet is shown to result from both surface and subsurface water flow at a site in the salt marsh portion of Louisiana's Barataria Bay Estuary. Chemical concentrations in marsh porewater, bayou water, marsh surface water remaining after marsh surface exposure by falling tides, and rivulet water are utilized to determine the source of water leaving the marsh during tidal exposure. The application of two-source mixing models to discharge chemical concentrations reveals that during the early, high flow portion of marsh surface runoff surface flow dominates discharge. Later, as discharge declines and subsurface pressure gradients increase, subsurface horizontal flow and seepage of porewater directly into the rivulet plays an increasing role in rivulet discharge. The contributions of porewater to the rivulet are shown to originate primarily in relatively shallow soils; porewater chemically similar to that found at a depth of 85 cm in the marsh is shown to contribute little to discharge.

The water surface drawdown resulting from the presence of the rivulet drainage system affects 22% of the marsh surface at this site, and has the potential to reduce soil anaerobiosis and plant stress. The discharge of porewater carries significant loads of dissolved chemicals to the estuary and potentially plays a role in the high productivity of Barataria Basin.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

CONCLUSIONS

A three-year study of the hydrology and sediment dynamics of a tidal bayou in the salt marsh zone of Louisiana's Barataria Bay Estuary has yielded an understanding of the major mechanisms of sediment flux and porewater discharge between the bayou and marsh and the adjacent shallow bay. The flux of suspended sediments into and out of the bayou included measurements of flux during all seasons of the year, and during both calm weather and stormy conditions. Continuous measurement of current velocity in the bayou and water level were measured using automatic equipment mounted on a scaffold platform mounted in midstream in the bayou. Water samples for TSS analysis were collected at the platform using an automatic water sampler. Water samples were collected at intervals of one to four hours during 5 periods ranging from several days to several weeks in duration. In addition to tidal fluxes during calm weather, measurements were collected during the passage of a tropical depression and two cold front passages. Suspended sediment flux data are compared to a variety of other data including water levels, weather data including wind speed and direction and rainfall, and sediment deposition and resuspension measurements collected by cooperating researchers at a site near the mouth of Ugly Shack Bayou.

Calm weather suspended sediment flux results in a net export of sediments throughout most of the year, with net imports occurring during the fall. Calm weather imports are the result of high water levels delivering sediments to the marsh surface where they are effectively trapped by marsh vegetation. At other times of the year, low water levels eliminate the marsh surface as a sediment sink, and net export of sediments result. Rainfall on the exposed marsh surface and low suspended sediment concentrations in the bay cause large summer export of sediments. Storms result in net imports throughout the year. Cold front passages occur frequently during the winter months of October through April, and result in large sediment imports due to strong prefrontal winds that cause water level setup and a resultant increase in inflow of water to the bayou. The water carries high concentrations of sediments resuspended by waves that also result form prefrontal winds. The frontal passage and resulting water level drop may remove significant amounts of sediment from the bayou, but on average the net flux due to cold fronts is in the inland direction. Wind storm during the fall, which are represented by the passage of Tropical Storm Dean (T.S. Dean) move large amounts of sediments into the bayou and marsh. These storms are the largest sediment dynamics events at the site, and have a considerable impact on the overall sediment budget of the marsh.

Sediment deposition in Live Oak bay, adjacent to Ugly Shack Bayou, follows a similar pattern to sediment flux in the bayou. Winter cold fronts result in sediment import to the bayou and also deposit sediment at the bay bottom site. Summer's calmer weather results in sediment export from the bayou and redistribution and removal of sediment from the bay bottom. Fall storms apparently resuspend sediments previously deposited in more exposed parts of the estuary and transport them to the Live Oak Bay site. At the same time large amounts of sediment move past the bay bottom site to be deposited in the bayou and marsh.

Ugly Shack Bayou is a net importer of sediments due to the large number of cold fronts that pass through the region every winter. The cumulative effects of the fronts outweighs the effects of more frequent but less powerful tidal fluctuations. Fall storm like T.S. Dean add to the net sediment import in the bayou. Net importation of sediments into the bayou and marsh follows the finding of earlier studies which demonstrate that Louisiana tidal marshes are rapidly accreting sediments.

Porewaters in the marsh adjacent to Ugly Shack Bayou are enriched in a variety of chemical constituents. Porewater and porewater constituents are exported from the marsh during low tide exposure of the marsh via a system of small rivulets that drain the marsh surface. These rivulets provide drainage to a large part of the marsh surface; water table drops more near the rivulet than elsewhere on the marsh, providing aeration to marsh soils. Rivulet discharge is a combination of surface runoff and subsurface flows that can be separated by chemical content. Surface runoff provided that high discharge rates early in the runoff cycle, awhile subsurface flow contributes mainly to low volume baseflow runoff. The behavior of the rivulet discharge is similar to the behavior of a river or stream draining a typical upland watershed. Surface flow and subsurface flow are equivalent to storm runoff and baseflow in upland watersheds. Porewater discharge has the potential to significantly impact the estuary by adding nutrients, metals, and other chemicals to estuarine waters.

RECOMMENDATIONS FOR FUTURE RESEARCH

As any research project should, this project raises many questions and illustrated many needs for additional research. Future research into sediment and carbon dynamics, storm frequency and influence in coastal marshes, and porewater fluxes are all indicated by the results presented here and will be discussed below.

Measurements of sediment flux, in combination with sediment deposition rates measured in Live Oak Bay indicate that sediment moves from the bay bottom into the bayou during storms, and in the reverse direction during calm summer conditions. Although TSS flux measurements indicate the magnitude and direction of sediment fluxes, they do not identify the sources of sediments. Similarly, VSS measurements do not indicate the source of carbon that in fluxes through the bayou. A variety of techniques have been employed to distinguish the sediments from various sources, and many of these could provide useful insight into bayou sediment dynamics. The ^{7}Be tracer techniques used by LUMCON researchers in their study of bay bottom sediments has been proposed as one method of identifying marsh sediments in bayou outflow. Marsh surface sediments should be enriched in 7 Be relative to bay bottom sediments, and their export would indicate active erosion is occurring on the marsh. In contrast, the presence of low Be sediments indicative of resuspended subsurface bay bottom sediments would indicate transport of sediments from estuarine water to the bayou.

Our measurements of sediment flux into the bayou do not distinguish sediments that eventually are deposited in the marsh from those that are deposited in the bayou. observations of the consistency of the bayou bottom suggest that soft sedimentary layers are periodically deposited and eroded from the bayou bottom. The collection of cores for ^7Be analysis similar to that carried out in the bay would help to quantify sediment deposition in the bay and clarify its role as a temporary storage site for sediments. Several techniques exist for measuring sediment deposition on marsh surfaces, and such measurements would serve to confirm the results of sediment flux studies in the bayou.

Our measurements of carbon transport in the bayou are largely indirect; VSS apparently represents a constant fraction of TSS and its transport is inferred from TSS flux. A variety of techniques to distinguish carbon compounds from various sources exist including stable carbon isotope ratio measurement, the identification of carbon compounds from terrestrial and marine sources and other techniques would potentially yield an understanding of the roles of various carbon sources in supplying carbon to the estuary.

Porewater exports measured here are preliminary and based on only a few days data. A sample of runoff from all seasons and a variety of weather conditions would support more precise estimation of annual porewater constituent export. In addition to more data, more detailed data would allow the use of additional techniques to distinguish surface and subsurface runoff. the large body of literature that examines runoff from upland watershed includes techniques that may be applicable to the marsh rivulet. For example, baseflow input to a stream plots as a straight line on a semi-log plot, permitting its separation form surface and storm runoff. More complete discharge hydrographs would allow application of this and other techniques to quantify subsurface discharge rates. Construction of a more complete model of rivulet discharge would yield more accurate estimates of the discharge of porewater constituents.

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DOCTORAL EXAMINATION AND DISSERTATION REPORT

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Title of Dissertation: Waterborne Materials Exchange between Marshes and Open Water of the Barataria Bay Estuary of Louisiana, U.S.A.

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